Refinishing porcelain surfaces after the use of two orthodontic bonding methods

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ABSTRACT

Introduction

The bonding and subsequent removal of an orthodontic bracket may damage the surface of a porcelain dental restoration. Refinishing the porcelain surface following orthodontic treatment is important for esthetics, maintaining structural integrity and minimizing the adhesion of dental plaque. The purpose of this study was to compare the damage to porcelain surfaces at debonding following the use of two bracket bonding methods, and to evaluate a porcelain refinishing procedure for restoring the porcelain surface to its original condition.

Materials and Methods

Forty porcelain discs were fabricated from Lava Ceram feldspathic porcelain veneer and divided equally into two orthodontic bracket bonding method groups. In the SB+HF+S group, the surface was deglazed by sandblasting and then etched with hydrofluoric acid gel. Porcelain conditioner silane coupling agent was applied followed by Transbond XT Light Cure Adhesive Primer. Stainless steel orthodontic brackets pre-coated with APC Plus composite adhesive were bonded. In the PA+S group, samples were treated with phosphoric acid and porcelain primer silane coupling agent and brackets were bonded as in the first group. After storage for 24 hours in water at 37°C, the brackets were debonded using anterior bracket removing pliers and residual resin was removed with a 12-fluted carbide bur. The refinishing procedure included polishing with an intra-oral porcelain polishing kit, followed by diamond polishing paste. Measurements of surface roughness, gloss and color were made with a surface profilometer, glossmeter and chromameter, respectively. The measurements were made on the porcelain discs of both groups prior to bonding brackets, after debonding and residual resin removal with the bur, after

refinishing with the porcelain polishing kit, and again following polishing with diamond paste. Data was analyzed with two way analysis of variance followed by Tukey HSD tests ($\alpha = 0.05$). In addition, specimens were examined under a scanning electron microscope to compare the surface roughness between stages of the bonding and polishing procedures.

Results

The sandblasting, hydrofluoric acid etch, and silane bonding method (SB+HF+S) caused significantly more ($P<0.001$) damage to the porcelain surface than the phosphoric acid and silane (PA+S) bonding method. The SB+HF+S bonding method significantly increased ($P<0.001$) porcelain surface roughness (0.160 to 1.121 μm), decreased gloss (41.3 to 3.7) and altered color ($\Delta E = 4.37$). The PA+S method significantly increased ($P<0.001$) porcelain surface roughness (0.173 to 0.341 μm), but the increase in Ra was significantly less ($P<0.001$) than that caused by the SB+HF+S bonding method. The PA+S method caused insignificant changes in gloss ($P = 0.602$) and color ($P = 0.972$). Damage inflicted on the porcelain surface was fully restorable to baseline values with the refinishing procedure tested, regardless of bonding method.

Conclusions

The PA+S bonding method is recommended over the SB+HF+S method if clinically satisfactory bond strengths are achieved, as the PA+S method causes significantly less damage to the porcelain surface. The protocol that we found worked well for refinishing the porcelain surface following orthodontic bracket debonding is to carefully remove residual adhesive with a carbide finishing bur, polish with an intra-oral porcelain polishing kit until the surface appears smooth, then polish with diamond polishing paste until the surface appears glossy.

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LITERATURE REVIEW

Porcelain Dental Restorations

The demand for dental esthetics is high, and as a result many adults are opting for porcelain dental restorations. Porcelain can now be used in many restorative situations including veneers, inlays and onlays, full coverage crowns, and as a veneer with all-ceramic bridges and porcelain-fused-to-metal restorations (Leinfelder, 2000). Low-fusing porcelains are currently used extensively and offer many advantages over traditional high-fusing porcelain systems. Low-fusing porcelains have the ability to be used as veneers in all-ceramic and porcelain-fused-to-metal restorations and have less potential for abrading opposing enamel, increased opalescence and translucency, and superior polishing (Leinfelder, 2000).

Bonding Orthodontic Brackets to Porcelain Dental Restorations

The demand for dental esthetics also has resulted in increasing numbers of adults seeking orthodontic treatment. The adult patient may have porcelain restorations that require bracket bonding and the orthodontist must produce adequate bond strength to retain the bracket for the duration of treatment.

Many laboratory studies have investigated strategies for bonding brackets to porcelain with clinically sufficient bond strength (Wood, *et al.*, 1986; Eustaquio, *et al.*, 1988; Smith, *et al.*, 1988; Whitlock, *et al.*, 1994; Zelos, *et al.*, 1994; Nebbe and Stein, 1996; Zachrisson, *et al.*, 1996; Gillis and Redlich, 1998; Bourke and Rock, 1999; Zachrisson, 2000; Harari, *et al.*, 2003; Pannes, *et al.*, 2003; Schmage, *et al.*, 2003; Ajlouni, *et al.*, 2005; Akova, *et al.*, 2005; Ferri, *et al.*, 2006; Larmour, *et al.*, 2006; Turk, *et al.*, 2006; Turkkahraman and Kucukesmen, 2006; Sarac, *et al.*, 2007; Karan, *et al.*, 2007). The materials and methods of these investigations, mean bonding strengths achieved, and standard deviations are listed in Appendix 1. The large number of studies dedicated to this clinical issue suggests the difficultly of retaining a bracket to a porcelain restoration and there is little agreement as to the best bonding protocol to use. All of these previously mentioned studies achieved the satisfactory 6-8 MPa (Bourke and Rock, 1999; Reynolds, 1975; Cochran, *et al.*, 1997) bond strength necessary for successful bonding of orthodontic brackets utilizing various surface treatments and bonding techniques. However, Zachrisson cautions that promising results from in vitro bond strength tests often do not translate into predictable clinical success (Zachrisson, *et al.*, 1996; Zachrisson, 2000). The continuous and increasing shear or tensile loads applied to the brackets in vitro do not mimic the in vivo force applications; and the variations in temperature, humidity, acidity, stresses and plaque found in the mouth cannot be accurately reproduced in laboratory experiments (Zachrisson, *et al.*, 1996; Zachrisson, 2000).

Many authors support the use of thermocycling regimens, such as 500 cycles in a water bath from 5°C to 55°C and back to 5°C, to help simulate temperature fluctuations found in the oral environment (Eustaquio, *et al.*, 1988; Zelos, *et al.*, 1994; Zachrisson, *et al.*, 1996; Bourke and Rock, 1999; Schmage, *et al.*, 2003; Akova, *et al.*, 2005; Turk, *et al.*, 2006; Turkkahraman and Kucukesmen, 2006; Sarac, *et al.*, 2007; Karan, *et al.*, 2007). Thermocycling has been found to significantly decrease bracket to porcelain bond strength (Eustaquio, *et al.*, 1988; Zachrisson, *et al.*, 1996; Bourke and Rock, 1999) due to differences in thermal expansion coefficients between porcelain, resin and metal resulting in stresses that cause bond failure (Zachrisson, *et al.*, 1996).

Orthodontic Bracket Bonding Techniques and Porcelain Surface Treatments

Some laboratory studies have concluded that deglazing the porcelain surface by mechanical roughening, utilizing methods such as sandblasting or diamond burs, enhances bond strengths through micromechanical retention (Wood, *et al.*, 1986; Smith, *et al.*, 1988; Zachrisson, *et al.*, 1996; Gillis and Redlich, 1998; Zachrisson, 2000; Schmage, *et al.*, 2003; Ajlouni, *et al.*, 2005; Turk, *et al.*, 2006). Others have found no advantage to deglazing the porcelain prior to bonding (Eustaquio, *et al.*, 1988; Zelos, *et al.*, 1994; Nebbe and Stein, 1996; Bourke and Rock, 1999; Pannes, *et al.*, 2003; Larmour, *et al.*, 2006). Porcelain surface preparation with hydrofluoric acid etching is cited by many authors as an important step for achieving good bond strength (Whitlock, *et al.*, 1994; Zachrisson, *et al.*, 1996; Gillis and Redlich, 1998; Zachrisson, 2000; Harari, *et al.*, 2003; Schmage, *et al.*, 2003; Ajlouni, *et al.*, 2005; Turkkahraman and Kucukesmen, 2006). However, hydrofluoric acid is a very strong acid that requires careful isolation of the working field to protect the patient (Zachrisson, *et al.*, 1996; Zachrisson, 2005). Others contend that treating the porcelain surface with phosphoric acid, which poses less risk to patients and staff, followed by silane treatment is sufficient (Nebbe and Stein, 1996; Bourke and Rock, 1999; Pannes, *et al.*, 2003; Larmour, *et al.*, 2006). Silica coating plus silane is another surface treatment regimen that has achieved excellent bond strengths in laboratory studies (Schmage, *et al.*, 2003; Karan, *et al.*, 2007). One study has evaluated conditioning porcelain with laser irradiation and found this enhanced bond strength (Akova, *et al.*, 2005).

Virtually all authors recommend treating the prepared porcelain surface with a silane coupling agent prior to bonding with an orthodontic adhesive system (Wood, *et al.*, 1986; Eustaquio, *et al.*, 1988; Smith, *et al.*, 1988; Whitlock, *et al.*, 1994; Zelos, *et al.*, 1994; Nebbe and

Stein, 1996; Gillis and Redlich, 1998; Bourke and Rock, 1999; Harari, *et al.*, 2003; Pannes, *et al.*, 2003; Ajlouni, *et al.*, 2005; Akova, *et al.*, 2005; Larmour, *et al.*, 2006; Turk, *et al.*, 2006; Turkkahraman and Kucukesmen, 2006; Karan, *et al.*, 2007). Silane primers form a chemical bridge between the inorganic porcelain surface and the organic resin adhesive (Bourke and Rock, 1999). However, multiple authors have found that adequate bond strengths could be achieved with hydrofluoric acid etching alone and silane treatment may not be necessary (Zachrisson, *et al.*, 1996; Schmage, *et al.*, 2003; Karan, *et al.*, 2007; Cochran, *et al.*, 1997). Indeed, Zachrisson stated that in vivo after sandblasting and hydrofluoric acid etching, silane application is optional (Zachrisson, 2000; Zachrisson, 2005). He found equivalent bond strengths to sandblasted porcelain using silane or hydrofluoric acid etching in vitro (Zachrisson, *et al.*, 1996). However, Zachrisson reported clinical findings that sandblasting plus silane did not produce acceptable bond strengths and were highly unreliable, while sandblasting and hydrofluoric acid etching of the porcelain (with or without silane) yielded excellent clinical results (Zachrisson, 2000). No other clinical reports were found in the literature.

<u>The Effects of Orthodontic Bracket Bonding and Debonding on the Porcelain Restoration</u>

Bonding orthodontic brackets to porcelain and subsequent debonding can result in significant damage or even fracture of the porcelain, (Wood, *et al.*, 1986; Eustaquio, *et al.*, 1988; Smith, *et al.*, 1988; Zelos, *et al.*, 1994; Nebbe and Stein, 1996; Zachrisson, *et al.*, 1996; Gillis and Redlich, 1998; Bourke and Rock, 1999; Schmage, *et al.*, 2003; Ajlouni, *et al.*, 2005; Ferri, *et al.*, 2006; Larmour, *et al.*, 2006; Turkkahraman and Kucukesmen, 2006; Cochran, *et al.*, 1997; Jarvis, *et al.*, 2006) especially when treated with surface roughening or hydrofluoric acid etching. Gillis and Redlich concluded that both porcelain surface conditioning and debonding may cause damage (Gillis and Redlich, 1998). Eustaquio et al. stated that irreversible damage to the porcelain surface may result from orthodontic bonding (Eustaquio, *et al.*, 1988). Jarvis et al. concluded that there is considerable change in porcelain surface roughness after debonding, as well as alterations in color (Jarvis, *et al.*, 2006). Many authors agree that porcelain surface defects caused by bracket debonding cannot be fully repaired (Gillis and Redlich, 1998). Patients need to be informed prior to bracket bonding that significant damage or fracture of the porcelain could occur at debond (Larmour, *et al.*, 2006; Jarvis, *et al.*, 2006).

Surface roughness determines the porcelain's strength unless a greater stress concentration occurs in the internal structure of the material (de Jager, *et al.*, 2000; Fischer, *et al.*, 2003). Surface flaws created by a procedure such as orthodontic bracket debonding and resin removal, could reduce porcelain strength and lead to fracture at lower force applications (de Jager, *et al.*, 2000; Fischer, *et al.*, 2003). The surface roughness of a ceramic also affects optical properties such as reflectance, or gloss (Shackleford, 1992). Increased porcelain surface roughness has also been correlated to increased dental plaque accumulation (Kawai, *et al.*, 2000). A roughened surface adversely affects the esthetics of a porcelain restoration and can attract staining factors (Jarvis, *et al.*, 2006). For these reasons, a porcelain restoration damaged by orthodontic bracket debonding should be refinished to a smooth surface.

<u>Refinishing Damaged Porcelain Surfaces</u>

Reports on various porcelain refinishing methods after orthodontic bracket debonding have been mixed. Smith et al. found that polishing porcelain with refinishing systems could not reproduce a glazed appearance (Smith, *et al.*, 1988). Eustaquio et al. stated that diamond polishing pastes restored the porcelain surface better than polishing stones, but nevertheless irreversible damage may result from the bonding procedure (Eustaquio, *et al.*, 1988). However, these studies are twenty years old and dental materials progressively evolve. Advances in dental porcelains have resulted in low-fusing porcelain systems that can be polished well (Leinfelder, 2000). Porcelain polishing kits also may have improved. Zelos et al. utilized scanning electron microscopy (SEM) and concluded that a porcelain adjustment kit and porcelain glaze polish could restore the porcelain surface after debonding (Zelos, *et al.*, 1994). Bourke and Rock also reported success with a diamond polishing paste after analysis with SEM (Bourke and Rock, 1999). Zacchrisson recommends slow-speed rubber polishing wheels followed by diamond polishing paste (Zachrisson, 2005). A more in depth analysis by Jarvis et al. utilized a stylus profilometer to assess surface roughness after orthodontic bracket debonding and polishing with a carbide bur and diamond polishing discs (Jarvis, *et al.*, 2006). They concluded that irreversible surface roughness changes occurred regardless of the polishing method used and that there is a need to standardize a porcelain polishing protocol after debonding (Jarvis, *et al.*, 2006). Sarac et al. used air-particle abrasion, hydrofluoric acid etching and silane for bonding orthodontic brackets and concluded that a porcelain adjustment kit plus diamond polishing paste could not return the porcelain surface to its original condition (Sarac, *et al.*, 2007). Another recent study (Karan and Toroglu, 2008) utilized a similar bracket bonding protocol and compared surface roughness after refinishing with Sof-Lex discs or a porcelain polishing wheel and polishing paste. The authors concluded that the porcelain polishing methods tested could not restore the original glazed surface (Karan and Toroglu, 2008). Materials, methods, mean surface roughness values and standard deviations for selected refinishing investigations are outlined in Appendix 2.

The prosthodontic literature offers some guidance. Two recent studies investigated refinishing porcelain surfaces following deglazing damage inflicted by a diamond bur (Wright, *et* *al.*, 2004; Sarac, *et al.*, 2006). The experiments are outlined in Appendix 3. After surface roughness analysis quantitatively with surface profilometry and qualitatively with SEM, both concluded that porcelain polishing systems could produce a surface as smooth as the original glazed porcelain (Wright, *et al.*, 2004; Sarac, *et al.*, 2006). Scurria and Powers obtained similar results utilizing finishing diamond points followed by diamond gels (Scurria and Powers, 1994). However, other older studies came to the opposite conclusion, that polishing cannot recreate the smoothness of the original porcelain glaze (Campbell, 1989; Patterson, *et al.*, 1991; Patterson, *et al.*, 1992). Changes in dental materials could account for the difference.

Objectives of the Current Study

The purpose of this study is to compare the damage to porcelain surfaces at debonding following the use of two orthodontic bracket bonding methods, and to evaluate a porcelain refinishing procedure for restoring the porcelain surface to its original condition. Specific objectives include: (1) Quantify the damage that results from orthodontic bracket bonding and debonding to feldspathic porcelain in terms of surface roughness, gloss and color changes. (2) Compare the damage to the porcelain surface resulting from two bracket bonding methods. (3) Test a porcelain polishing method and determine if surface roughness, gloss and color can be fully restored. (4) Develop a protocol recommendation for refinishing porcelain for the orthodontic specialist.

HYPOTHESIS

Hypothesis 1: After the porcelain is bonded with orthodontic brackets and debonded, the surface will exhibit significant changes in roughness, gloss and color as compared to the pre-bonding measurements.

Null hypothesis 1: After debonding, the porcelain surface will exhibit insignificant changes in roughness, gloss and color as compared to the pre-bonding measurements.

Hypothesis 2: After residual resin clean-up with a 12-fluted tungsten carbide bur, samples bonded with sandblasting, hydrofluoric acid and silane will exhibit significantly more damage to the porcelain surface than the group bonded with phosphoric acid and silane.

Null hypothesis 2: The null hypothesis is there will be no significant differences between bonding method groups.

Hypothesis 3: Subsequent polishing with the porcelain polishing kit and diamond polishing paste will progressively lead to refinished surfaces that will have insignificant differences in surface roughness, gloss and color from the undamaged control samples.

Null hypothesis 3: The porcelain surfaces cannot be restored regardless of bonding method or polishing stage.

MATERIALS AND METHODS

Forty porcelain specimens were fabricated from Lava Ceram feldspathic porcelain veneer (shade A3, 25 µm grain size, 3M ESPE, St. Paul, MN) by Dahlin/Fernandez/Fritz Dental Laboratory, Inc. (Portland, OR). Lava Ceram is used as the veneer for Lava zirconia frameworks in the manufacture of Lava all-ceramic dental restorations. The porcelain specimens were fabricated using a metal cylinder as a mold to form porcelain discs approximately 10 mm in diameter and 2 mm thick. The firing procedure began with a starting temperature of 500°C. The porcelain discs were fired to 925°C under vacuum with a heat rate of 75°C per minute, and air fired at 925°C for 30 seconds to obtain an autoglaze. The 40 porcelain discs were divided into two orthodontic bracket bonding method groups of 20 samples each. Prior to bonding brackets to the porcelain samples, baseline control data for surface roughness, gloss, and color was collected for the glazed surfaces (see below).

Bonding Method 1: Sandblasting, Hydrofluoric Acid and Silane (SB+HF+S)

Twenty of the porcelain discs were prepared for bonding an orthodontic bracket as recommended by Zachrisson (Zachrisson, 2000; Zachrisson, 2005). Materials used are shown in Table 1. An area approximately the size of the bracket base was deglazed by sandblasting with an intraoral Microetcher IIA (Danville Materials, Inc., San Ramon, CA) with 50 micron aluminum oxide for 3 seconds. The porcelain surfaces were then rinsed with water for 5 seconds, air dried for 10 seconds, and etched with Porc-Etch 4% hydrofluoric acid gel (Reliance Orthodontic Products, Inc., Itasca, IL) for 4 minutes. The hydrofluoric acid gel was wiped off the surfaces with a cotton roll. Samples were then rinsed with water for 5 seconds and air dried for 10 seconds. Porcelain Conditioner silane coupling agent (Reliance Orthodontic Products, Inc., Itasca, IL) was applied for 60 seconds followed by Transbond XT Light Cure Adhesive Primer (3M/Unitek Corp., Monrovia, CA). Upper right central incisor stainless steel orthodontic brackets (Victory Series, MBT Low Profile .022x.028 inch slot, 3M/Unitek Corp., Monrovia, CA) pre-coated with APC Plus composite adhesive were placed in the center of the porcelain samples. Using an explorer, the brackets were firmly compressed against the porcelain surfaces with a force in the range of 12-14 N. Excess adhesive was carefully removed with an explorer prior to curing. The specimens were light cured with a LED curing light (Ortholux, 3M/Unitek Corp., Monrovia, CA) operating at 800 mW/cm² for 20 seconds on both mesial and distal of the brackets, resulting in a total cure time of 40 seconds.

Bonding Method 2: Phosphoric Acid and Silane (PA+S)

The other group of twenty porcelain discs was bonded using a second method leaving the glazed surface intact. Materials used are shown in Table 2. These samples were treated for 60 seconds with phosphoric acid Etching Solution (Ormco Corp., Glendora, CA) to acidify the surface. The etching solution was not rinsed off in accordance with the manufacturer's instructions. Two coats of Porcelain Primer silane coupling agent (Ormco Corp., Glendora, CA) were then applied with a cotton pellet. The primed porcelain surfaces were left undisturbed for one minute and then rinsed with water spray for 5 seconds and air dried for 10 seconds in accordance with the manufacturer's instructions. Transbond XT Light Cure Adhesive Primer was applied to the primed porcelain surface. Upper right central incisor stainless steel orthodontic brackets pre-coated with APC Plus adhesive were placed and cured in the same manner as the first group. All porcelain samples from both groups were stored for 24 hours in water at 37°C after bonding brackets.

Orthodontic Bracket Debonding, Adhesive Removal and Porcelain Refinishing

In order to simulate clinical procedures, the brackets on the porcelain samples were debonded by the same operator using anterior bracket removing pliers (#098-SL, Orthopli Corp., Philadelphia, PA). A gentle peeling force was applied while squeezing the tie-wings and distorting the bracket (Zachrisson, 2005). Bond strength was not investigated as several laboratory studies have previously found clinically adequate bond strengths (6-8 MPa or greater) using SB+HF+S (Zachrisson, *et al.*, 1996; Bourke and Rock, 1999; Ajlouni, *et al.*, 2005) and PA+S (Nebbe and Stein, 1996; Bourke and Rock, 1999; Pannes, *et al.*, 2003; Larmour, *et al.*, 2006). Materials used in the refinishing procedure are shown in Table 3. The samples from both bonding method groups had residual resin adhesive carefully removed from the porcelain surface with a 12-fluted tungsten carbide bur (US# 7404 Football, Brasseler, Savannah, GA) in a high-speed handpiece (StarDental, Lancaster, PA). Great care was taken to avoid inflicting unnecessary damage on the porcelain specimens with the bur. A new bur was used for every ten samples. All samples were rinsed with water for 5 seconds and air dried for 10 seconds after resin removal. The porcelain discs were then measured for surface roughness, gloss, and color as described in the next sections. Porcelain samples from both groups were polished with the Intra-Oral Dialite Porcelain Adjustment Polishing Kit (Brasseler, Savannah, GA) series of Reduce Polish (blue), Pre-Polish (pink), and High Gloss (gray) polishing wheels with a slow-speed handpiece (StarDental, Lancaster, PA). In order to simulate clinical procedures, all polishing was performed by the same operator until the porcelain surface appeared visually smooth and glossy (Sarac, *et al.*, 2007; Jarvis, *et al.*, 2006; Karan and Toroglu, 2008; Wright, *et al.*, 2004). Approximately 60-90 seconds was spent with each polishing wheel using moderate pressure.

Following the porcelain polishing kit procedure, the samples were rinsed with water for 5 seconds and air dried for 10 seconds. Measurements for surface roughness, gloss, and color were then repeated on all samples. The final step in the refinishing procedure was diamond polishing paste (Truluster Polishing System for Porcelain, grain size 2-5 μm, Brasseler, Savannah, GA) applied with a small felt wheel on a slow-speed handpiece. Again, polishing was performed until a visually smooth and shiny surface was produced. Samples were initially polished at a very low speed (approximately 3000 rpm) with moderate pressure, and then buffed at higher speed (approximately 10,000-15,000 rpm) with very light pressure. Roughly 60-90 seconds were spent polishing with the diamond paste on each specimen. All porcelain samples were then given a final rinse with water for 5 seconds, air dried for 10 seconds, and measurements for surface roughness, gloss, and color recorded.

Surface Roughness Measurements (Ra)

Surface roughness was measured using a surface profilometer (TR200 Surface Roughness Tester, TIME Group Inc., Beijing, China). Ra is the average surface roughness over a defined distance and is measured in micrometers (μm). The profilometer was set to five cutoffs of 0.25mm each for a total length measured of 1.25mm. The profilometer was calibrated with a standard reference specimen (Ra = 1.61 μm) and calibration was re-checked after every ten samples measured. Each porcelain sample was placed in a paralleling device to insure that the specimen's test surface was parallel to the bench top and the profilometer prior to taking Ra measurements. Each porcelain disc was measured three times (length, width, and diagonal) and the values averaged to give a mean Ra value. Surface roughness measurements were taken on all porcelain samples prior to bonding (controls), after bracket debonding and residual resin removal with a 12-fluted carbide bur, after polishing with the intraoral porcelain polishing kit, and again following final refinishing with diamond polishing paste.

Gloss Measurements

Gloss values were measured with a glossmeter (Novo-Curve, Rhopoint Instrumentation, East Sussex, UK). The glossmeter measures the percentage of incident light reflected from the porcelain surface and is recorded in gloss units on a scale from 0 to 100. The light is projected at an inclination of 60° to the porcelain surface and covers an area of 2mm x 2mm. The glossmeter was calibrated with a standard reference specimen measuring 93.9 gloss units and calibration was re-checked after every ten samples measured. Five gloss measurements were taken for each porcelain disc and the sample was moved slightly over the aperture between each measurement. Only the highest gloss reading for each specimen was recorded. Gloss measurements were taken on all porcelain samples between the steps in the bonding and refinishing procedure previously described.

Color Measurements

Color was analyzed using a chromameter (ChromaMeter CR-221, Minolta Co., Osaka, Japan). The chromameter was calibrated according to the manufacturer's instructions with a standard reference specimen measuring L* = 99.66, a* = -0.41, b* = 2.89, and was recalibrated after every ten samples measured. Measurements were made using the CIE L*a*b* color system (Commission Internationale l'Eclairage, 1986). L*a*b* are chromaticity coordinates that together describe color. L* is the measure for lightness, or black (-L*) to white (+L*); while a* measures green (-a*) to red (+a*), and b* measures blue (-b*) to yellow (+b*) (Sarac, *et al.*, 2006; Powers, 2002). Measurements of L*, a* and b* are made on a scale from -100 to +100. Color differences (ΔE) were determined with the following formula: (Sarac, *et al.*, 2006; Powers, 2002)

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

A value of ΔE between 1 and 3.3 may be observed clinically, but is acceptable (Sarac, *et al.*, 2006). A value of ΔE equal to or greater than 3.3 is considered clinically unacceptable (Sarac, *et al.*, 2006; Powers, 2002).

Scanning Electron Microscope Analysis

Representative porcelain specimens from each bonding group, as well as undamaged control samples, were examined under a scanning electron microscope (Quanta 200, FEI Company, Hillsboro, OR) at 500x to qualitatively compare surface roughness at the various stages of the refinishing procedure. The scanning electron microscope was set at low vacuum (less than 1 torr) and 12.50 kV. The porcelain samples were not coated for the SEM analysis.

Statistical Analysis

Data was analyzed with two way analysis of variance followed by Tukey HSD tests (α = 0.05). The variables were bonding method and polishing stage.

Error Analysis

An error analysis was conducted to test for random and systematic errors. Five samples were selected randomly from each bonding method group and were re-tested for surface roughness, gloss and color at each stage of the refinishing procedure. Random error was assessed using the Dahlberg Formula (Dahlberg, 1940).

$$S_e^2 = \Sigma d^2/2n$$

The mean square error is represented by S_e^2, where d is the difference between the repeated measurements and n is the number of samples re-tested. Systematic errors were assessed using paired t-tests comparing the original data with the re-test data (Houston, 1983).

RESULTS

One sample of the 20 in the PA+S group fractured upon debond. A piece of porcelain approximately the size of the bracket base fractured off of the sample and remained bonded to the bracket. The sample could not be measured with the testing equipment and it was impossible to restore the remaining surface by polishing. Therefore, this sample was removed from the analysis thereby reducing the sample size for the PA+S group to 19. Complete data, means and standard deviations are shown in Appendix 4.

Two way analysis of variance showed significant differences between bonding method groups ($P<0.001$) and polishing stages ($P<0.001$), as well as significant interaction between them (bonding x polishing, $P<0.001$) for surface roughness, gloss and color change. Two way analysis of variance worksheets are shown in Appendix 5.

Mean porcelain surface roughness (Ra) values for both bonding method groups are shown in Figure 1. Surface roughness was significantly affected in both bonding method groups. In the SB+HF+S group, there was a large increase in Ra after debond and residual resin removal with a finishing bur as compared to the pre-bond glazed surface ($P<0.001$). The polishing kit failed to return Ra to baseline ($P=0.025$). The diamond polishing paste further improved Ra to that of the controls ($P=0.755$). In the PA+S group, there also was a significant increase in surface roughness after debond and residual resin removal as compared to controls ($P<0.001$). However, the increase in Ra found in the PA+S group at debond was significantly less than that found in the SB+HF+S group ($P<0.001$). The polishing kit restored the Ra in the PA+S group to that of the controls ($P=0.969$). The diamond polishing paste did not significantly improve the Ra in this group ($P=0.824$).

Mean porcelain gloss values are shown in Figure 2. In the SB+HF+S group, there was a large decrease in gloss ($P<0.001$) after debond and residual resin removal with a finishing bur. The polishing kit improved the gloss value but did not restore it to the control value ($P<0.001$). After polishing with the diamond polishing paste, the gloss value significantly exceeded that of the control ($P<0.001$). In the PA+S group, there was no difference compared to the controls after debond ($P=0.602$), the gloss was not significantly affected. The polishing kit resulted in a decrease in the gloss as compared to controls ($P<0.001$). After polishing with the diamond polishing paste, the gloss value significantly exceeded that of the control ($P<0.001$).

Mean porcelain color change (ΔE) values are shown in Figure 3. In the SB+HF+S group, color was significantly altered ($P<0.001$) after debond and residual resin removal with a finishing bur. In general, the SB+HF samples became noticeably lighter (increased L*) and less yellow (decreased b*) with an average ΔE of 4.37. This was beyond the threshold for clinical acceptability of 3.3 and was visually perceptible. The porcelain polishing kit improved ΔE to a mean of 1.39 but could not completely restore it ($P<0.001$). Subsequent polishing with the diamond polishing paste reduced ΔE to a mean of 0.44. This was less than the visually perceptible minimum of 1.0, therefore the color was fully restored. In the PA+S group, no significant change in color was found at any stage of the bonding or refinishing procedure.

Error analysis showed random error averaged 0.039 µm for Ra, 2.67 gloss units for gloss and 0.176 L*, 0.059 a*, 0.106 b* for color ($\Delta E=0.21$). Systematic error was assessed with paired t-tests and showed no differences ($P<0.05$) between the original and repeated measures for both groups at all stages of refinishing.

Scanning electron microscope analysis confirmed the quantitative porcelain surface roughness results. The autoglazed porcelain surface appeared smooth with a few random small pits and irregularities. The pre-bond SB+HF+S etched surface appeared uniformly very rough with small chips, pits and fissures (Figure 4). The SB+HF+S surface after debond and residual resin removal with a finishing bur appeared similarly rough. The SB+HF+S porcelain surface at the polishing kit stage appeared mostly smooth but with some scratch marks and pits evident. After further polishing with the diamond paste, the surface appears similar to the autoglazed sample. The PA+S group images showed a mildly damaged surface after debond (Figure 5). The porcelain surface was mostly smooth with some scuff marks from the bur, resin remnants, and cracks visible. After refinishing with the polishing kit followed by diamond polishing paste, PA+S group surface appeared progressively smoother.

DISCUSSION

It has been demonstrated that debonding orthodontic brackets from a porcelain surface can result in significant damage and even fracture of the porcelain. Selection of a porcelain bonding method that delivers adequate strength but minimizes damage, and selection of a refinishing procedure that can restore the porcelain surface is important for several reasons. Increased surface roughness decreases the porcelain's flexural strength, so surface flaws could lead to fracture at a lower stress (de Jager, *et al.*, 2000; Fischer, *et al.*, 2003). Rougher porcelain surfaces can lead to increased dental plaque accumulation (Kawai, *et al.*, 2000). Surface roughness impacts gloss (Shackleford, 1992), color (Powers, 2002), and can attract staining factors (Jarvis, *et al.*, 2006). Thus, the esthetics of the porcelain dental restoration can be adversely affected.

The bracket bonding method selected directly impacts the damage inflicted on the porcelain surface. Sandblasting and hydrofluoric acid etching are designed to roughen the porcelain surface to increase the surface area available for micromechanical and chemical retention (Zelos, *et al.*, 1994; Zachrisson, *et al.*, 1996). The sandblasting, hydrofluoric acid etching and silane technique resulted in large changes in gloss, surface roughness, and color. Several recent studies (Sarac, *et al.*, 2007; Jarvis, *et al.*, 2006; Karan and Toroglu, 2008) have tested bonding methods that included either sandblasting or hydrofluoric acid etching and all concluded that the tested refinishing procedures could improve surface roughness, but could not restore the porcelain surface to its original condition. The refinishing procedures tested in these studies included: carbide burs and Sof-Lex discs (Jarvis, *et al.*, 2006), an adjustment kit and diamond polishing paste (Sarac, *et al.*, 2007), and Sof-Lex discs and a polishing wheel with polishing paste (Karan and Toroglu, 2008). The results of this experiment suggest that porcelain surfaces treated with sandblasting, hydrofluoric acid, and silane prior to bracket bonding can be restored to the original surface roughness, gloss, and color by refinishing with an intra-oral porcelain polishing kit followed by diamond polishing paste. Several other studies agree that even significant damage to the porcelain inflicted by sandblasting, HF etching, or burs can be fully restored by polishing with porcelain polishing kits and diamond polishing paste (Bourke and Rock, 1999; Wright, *et al.*, 2004; Sarac, *et al.*, 2006).

In contrast to sandblasting and hydrofluoric acid etching, phosphoric acid etching of porcelain is not designed to roughen the surface but to clean and neutralize the alkalinity of the surface, thereby enhancing the chemical activity of the silane primer (Nebbe and Stein, 1996; Bourke and Rock, 1999; Wolf, *et al.*, 1993). The phosphoric acid and silane porcelain primer bonding method caused much less damage to the porcelain surface than the sandblasting and hydrofluoric acid etching technique. This finding agrees with other studies (Bourke and Rock, 1999; Ajlouni, *et al.*, 2005). The phosphoric acid and porcelain primer bonding method caused insignificant changes in gloss and color. It did cause a significant change in surface roughness that was restorable.

Several subjective observations were made during the bonding and manual debonding procedure. It was important to fully compress the bracket against the porcelain surface during bonding to extrude all excess composite adhesive out from under the bracket. The excess adhesive was carefully removed with an explorer prior to curing. This minimized the amount of adhesive that required removal with a bur at debonding; an important factor since the bur was capable of causing further damage to the porcelain surface. The composite adhesive was difficult to remove from the porcelain in the SB+HF+S group and required considerable grinding with the 12-fluted tungsten carbide bur. The adhesive remaining on the porcelain surface was much easier to remove in the PA+S group, with much of it simply flaking away as the bur contacted it. In fact, considerable care needed to be taken to avoid inflicting unnecessary damage on the porcelain surface. However, the one sample that experienced fracture upon debond was from the PA+S group, suggesting appreciable bond strength. It was presumed that the sample may have been defective; perhaps a large air bubble was hidden below the surface.

This experiment did not investigate bracket bond strength to the porcelain surface since numerous previous studies have explored that topic (Wood, *et al.*, 1986; Eustaquio, *et al.*, 1988; Smith, *et al.*, 1988; Whitlock, *et al.*, 1994; Zelos, *et al.*, 1994; Nebbe and Stein, 1996; Zachrisson, *et al.*, 1996; Gillis and Redlich, 1998; Bourke and Rock, 1999; Zachrisson, 2000; Harari, *et al.*, 2003; Pannes, *et al.*, 2003; Schmage, *et al.*, 2003; Ajlouni, *et al.*, 2005; Akova, *et al.*, 2005; Ferri, *et al.*, 2006; Larmour, *et al.*, 2006; Turk, *et al.*, 2006; Turkkahraman and Kucukesmen, 2006; Sarac, *et al.*, 2007; Karan, *et al.*, 2007). Many laboratory experiments conclude that treating the porcelain surface with phosphoric acid followed by silane application, as in the PA+S group, results in sufficient bond strength (Nebbe and Stein, 1996; Bourke and Rock, 1999; Pannes, *et al.*, 2003; Larmour, *et al.*, 2006). However, the subjective observations made in this study suggest that higher bond strengths were achieved in the SB+HF+S group with more composite adhesive left bonded to the porcelain surface after bracket removal. In general, we found the SB+HF+S samples were noticeably more difficult to debond and much of the adhesive was left bonded to the porcelain. In contrast, the PA+S group samples were easier to debond and less composite adhesive was left adhering to the porcelain. These observations coincide with the data of Bourke and Rock that SB+HF+S achieved high bond strength and increased Adhesive Remnant Index scores and Porcelain Fracture Index scores (Bourke and Rock, 1999). Zachrisson contends that SB+HF are essential for adequate clinical bonding and warns that promising results from laboratory bond strength tests often do not translate into predictable clinical success (Zachrisson, *et al.*, 1996; Zachrisson, 2000). The continuous and increasing shear or tensile loads applied to the brackets by testing machines do not mimic the in vivo force applications; and the variations in temperature, humidity, acidity, stresses and plaque found in the mouth cannot be accurately reproduced in laboratory experiments (Zachrisson, *et al.*, 1996; Zachrisson, 2000). In the clinic, a prudent course may be to begin with the PA+S method to minimize damage to the porcelain. If the bracket bond fails repeatedly, the clinician could progress to the SB+HF+S bonding method, or band the tooth. Achieving satisfactory bracket to porcelain bond strengths may be more challenging in the mandibular arch where brackets potentially are subjected to more direct occlusal forces (Zachrisson, 2000).

Surface roughness strongly influences both the gloss and the color of the porcelain surface. Rough surfaces result in diffuse reflection and the surfaces appears less glossy, where as very smooth surfaces result in specular reflection and will exhibit higher gloss (Shackleford, 1992). In a clinical situation, the rough porcelain surface is usually wet. Moisture can fill the crevices of a rough surface increasing the amount of specular reflection and thereby improving the gloss (Tanaka, *et al.*, 1985; Henderson, 2007). Similarly, color is affected by surface roughness. Some white light is directly reflected off the surface and mixes with the light reflected from the body of the porcelain. More white light is directly reflected off a very rough surface diluting the color and resulting in a lighter appearance (Powers, 2002). This explains why the porcelain surfaces severely roughened with SB+HF+S concurrently experienced large decreases in gloss and color changes; and why polishing restored them. This study suggests that both the porcelain polishing kit and the diamond polishing paste are necessary to fully restore surface roughness, gloss and color to the original condition.

In this study, efforts were made to simulate clinical procedures. Therefore, brackets were gently debonded by hand using anterior bracket removing pliers rather than utilizing a testing machine with continuous and increasing tensile or shear loads (Zachrisson, *et al.*, 1996; Zachrisson, 2000; Zachrisson, 2005). Polishing was performed without artificial time constraints until the porcelain surface appeared glossy and smooth to the naked eye. Many studies have used this approach to simulate a clinical situation (Sarac, *et al.*, 2007; Jarvis, *et al.*, 2006; Karan and Toroglu, 2008; Wright, *et al.*, 2004).

This study had several limitations. Although considerable effort was made to simulate clinical procedures, this was nevertheless a laboratory experiment and the samples were never subjected to the complexities of the oral environment. As mentioned previously, bond strengths were not investigated and only one type of porcelain polishing kit and diamond polishing paste were tested. The porcelain samples used in this experiment were not perfectly flat but had slightly varying convex surfaces. This resulted in some variability with gloss measurements and was reflected in the standard deviations. The polishing procedures may have flattened the porcelain surfaces somewhat and may partially explain why gloss values after diamond polishing paste exceeded those of the controls.

The phosphoric acid and silane bonding method is recommended over the sandblasting, hydrofluoric acid etch, and silane technique if clinically satisfactory bond strengths are achieved, since the PA+S method causes significantly less damage to the porcelain surface. Future research could include testing different types of dental porcelains, different porcelain conditioning methods and bonding systems, and various composite adhesives. In addition, multiple porcelain refinishing systems are commercially available and could be compared.

CONCLUSIONS

- The sandblasting, hydrofluoric acid etching, and silane bonding method caused significantly more damage to the porcelain surface than the phosphoric acid and silane method.
- The sandblasting, hydrofluoric acid etching, and silane bonding method significantly increased porcelain surface roughness, decreased gloss and altered color.
- The phosphoric acid and silane method significantly increased porcelain surface roughness, but the increase in Ra was significantly less than that caused by the sandblasting, hydrofluoric acid etch, and silane bonding method.
- The phosphoric acid and silane method caused insignificant changes in gloss and color.
- Damage inflicted on the porcelain surface was fully restorable to baseline values with the refinishing procedure tested, regardless of bonding method.
- The phosphoric acid and silane bonding method is recommended if clinically satisfactory bond strengths are achieved, since this method causes significantly less damage to the porcelain surface than the sandblasting, hydrofluoric acid etching, and silane bonding method.
- The recommended protocol for refinishing the porcelain surface following orthodontic bracket debonding is: (1) careful removal of residual resin adhesive with a carbide finishing bur. (2) polishing with an intra-oral porcelain polishing kit until the surface appears smooth. (3) polishing with diamond polishing paste on a small felt wheel until the surface appears glossy.

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Table 1. Materials used in the sandblasting, hydrofluoric acid and silane (SB+HF+S) bonding group.

Product	Material (% by wt)	Manufacturer	Lot Number
Microetcher IIA	Intraoral Sandblaster	Danville Materials, Inc.	11691-2
Aluminum Oxide	Al_2O_3 (50 μm)	Danville Materials, Inc.	12279-4
Porc-Etch	Hydrofluoric Acid, 4%	Reliance Orthodontic Products, Inc.	0704406
Porcelain Conditioner	Silane, 1-10% Ethanol, 30-70% Acetone, 30-70%	Reliance Orthodontic Products, Inc.	0704401
Transbond XT Primer	Trethylene glycol dimethacrylate, 45-55% Bisphenol A diglycidyl ether dimethacrylate, 45-55%	3M/Unitek Corp.	7EH
APC Plus Adhesive	Quartz reaction product with hydrolyzed silane, 35-45% Glass reacted with hydrolyzed silane, 35-45% Polyethylene glycol dimethacrylate, 5-15% Citric acid dimethacrylate oligomer, 5-10% Bisphenol A diglycidyl ether dimethacrylate, 1-10% Dimethyl siloxane, reaction product with silica, 1-5%	3M/Unitek Corp.	Z1188

Source: Material Safety Data Sheets provided by manufacturers and product labels.

Table 2. Materials used in the Phosphoric Acid and Silane (PA+S) bonding group.

Product	Material (% by wt)	Manufacturer	Lot Number
Etching Solution	Phosphoric acid, 37% Water	Ormco Corp.	5F1
Porcelain Primer	Organosilane Ester, 15-20% Ethanol, 80-85%	Ormco Corp.	7E1
Transbond XT Primer	See Table 1.	3M/Unitek Corp.	7EH
APC Plus Adhesive	See Table 1.	3M/Unitek Corp.	Z1188

Source: Material Safety Data Sheets provided by manufacturers and product labels.

Table 3. Materials used in the refinishing procedure.

Product	Material	Manufacturer	Lot Number
US# 7404 Football	12-fluted tungsten carbide bur	Brasseler	14164
Intra-Oral Dialite Porcelain Adjustment Polishing Kit	Reduce Polish (blue) wheel Pre-Polish (pink) wheel High Gloss (gray) wheel	Brasseler	Unavailable
Truluster Polishing System for Porcelain	Diamond polishing paste (grain size 2-5 μm)	Brasseler	H3841

Source: Product labels.

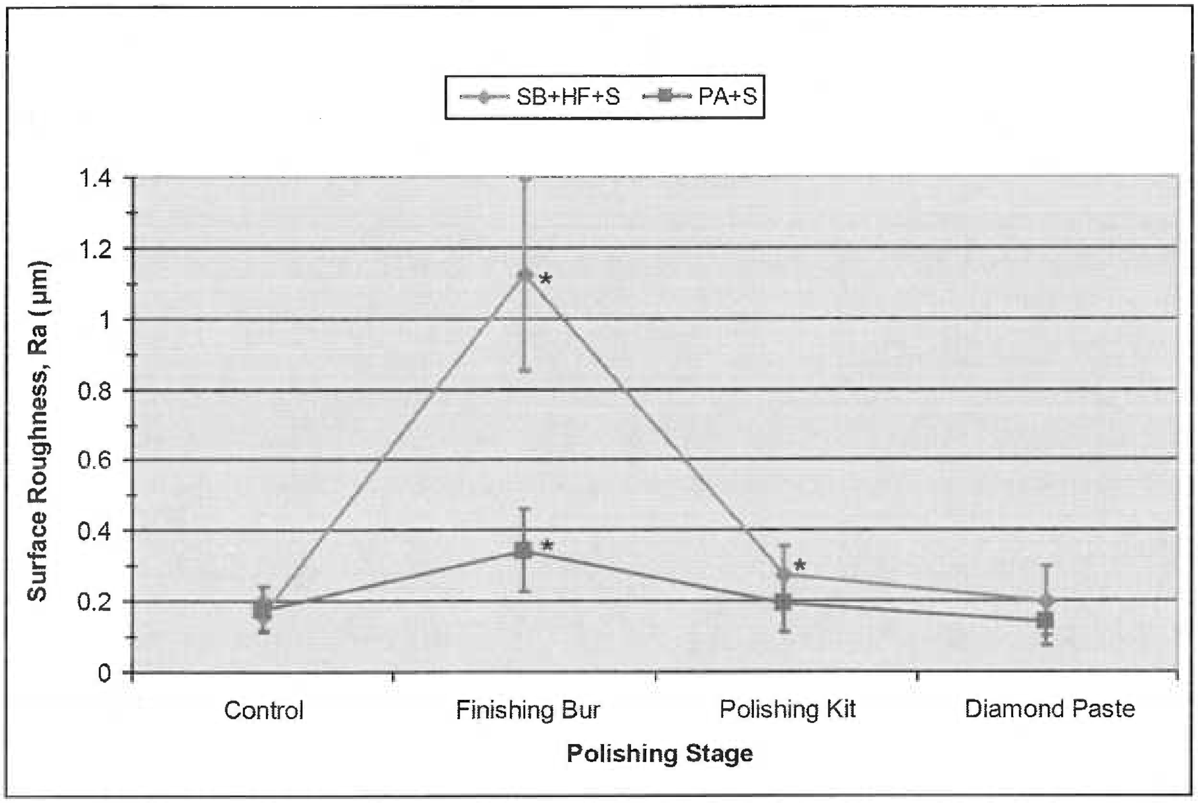

Figure 1. Mean surface roughness values with standard deviation bars. Statistically significant differences from the control are indicated by an asterisk. $^*P<0.05$.

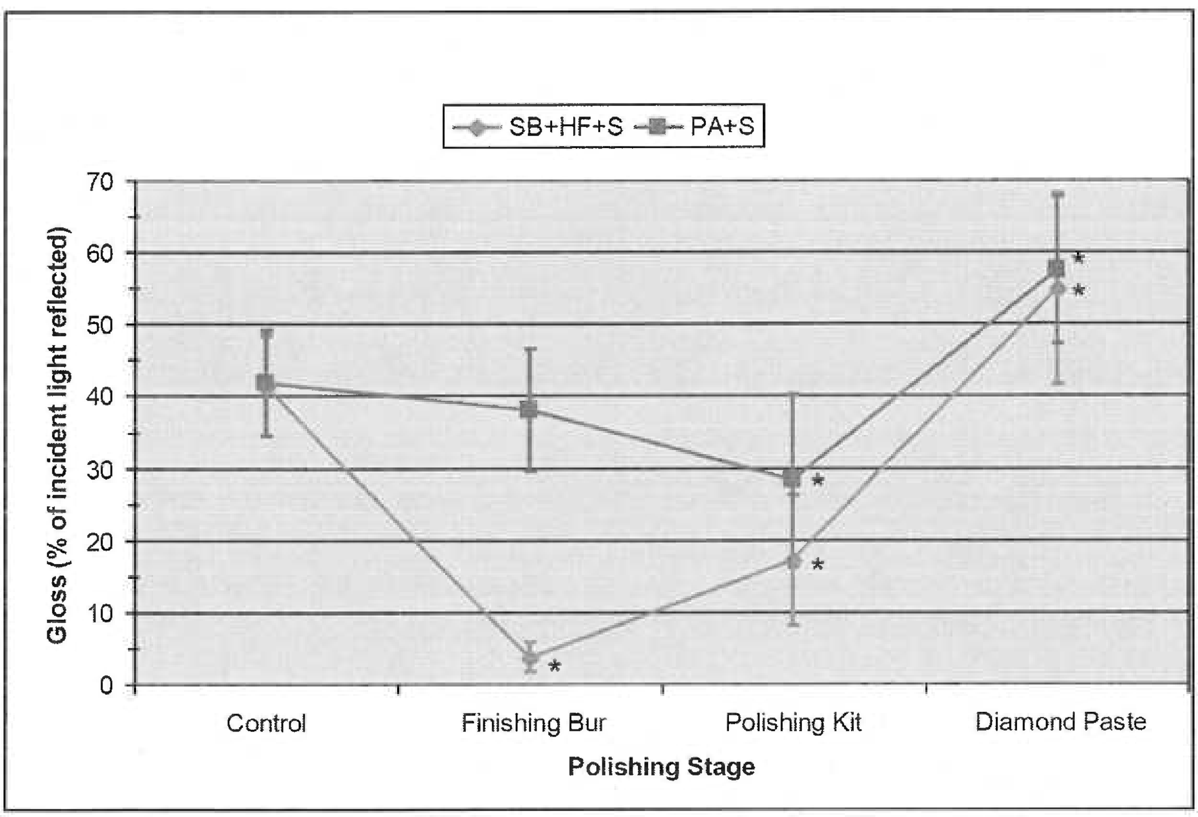

Figure 2. Mean gloss values with standard deviation bars. Statistically significant differences from the control are indicated by an asterisk. $^*P<0.05$.

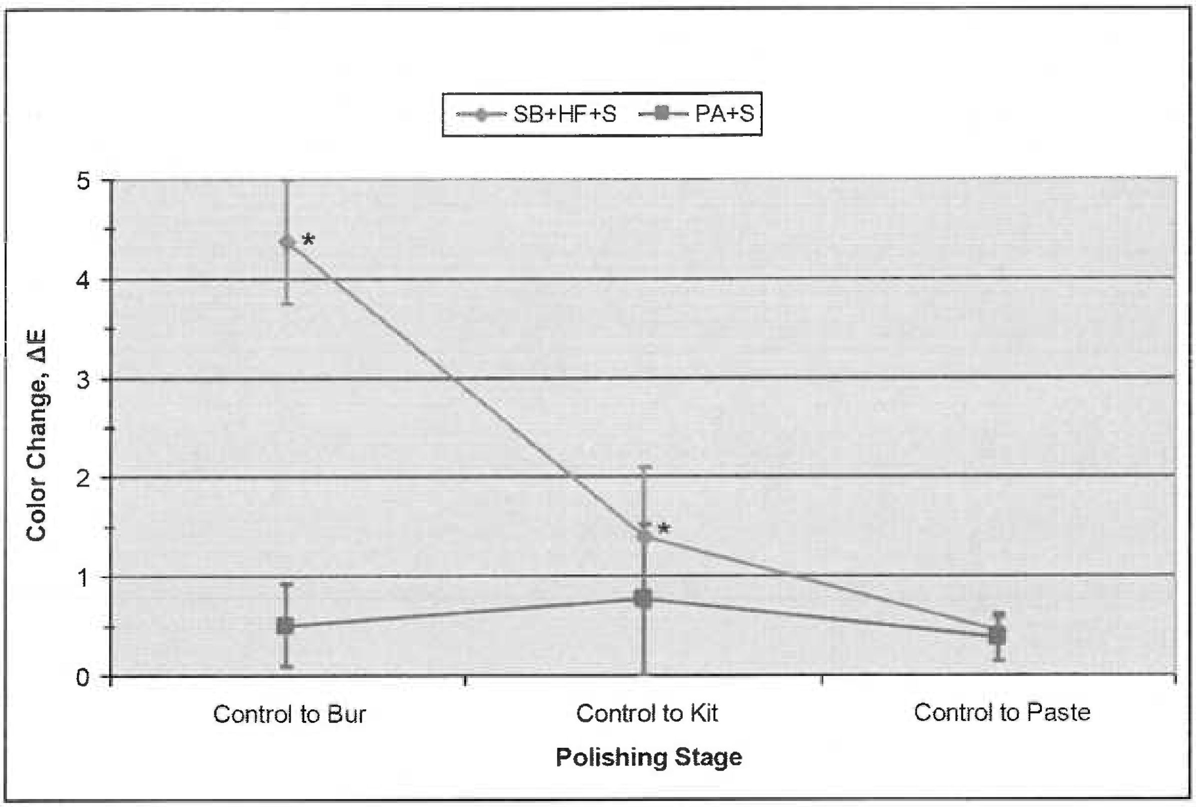

Figure 3. Mean color change (ΔE) values with standard deviation bars. ΔE values greater than 3.3 are considered clinically significant. ΔE values between 1 and 3.3 may be observed clinically, but are acceptable. Significant differences from the control to paste group are indicated by an asterisk. *P<0.05.

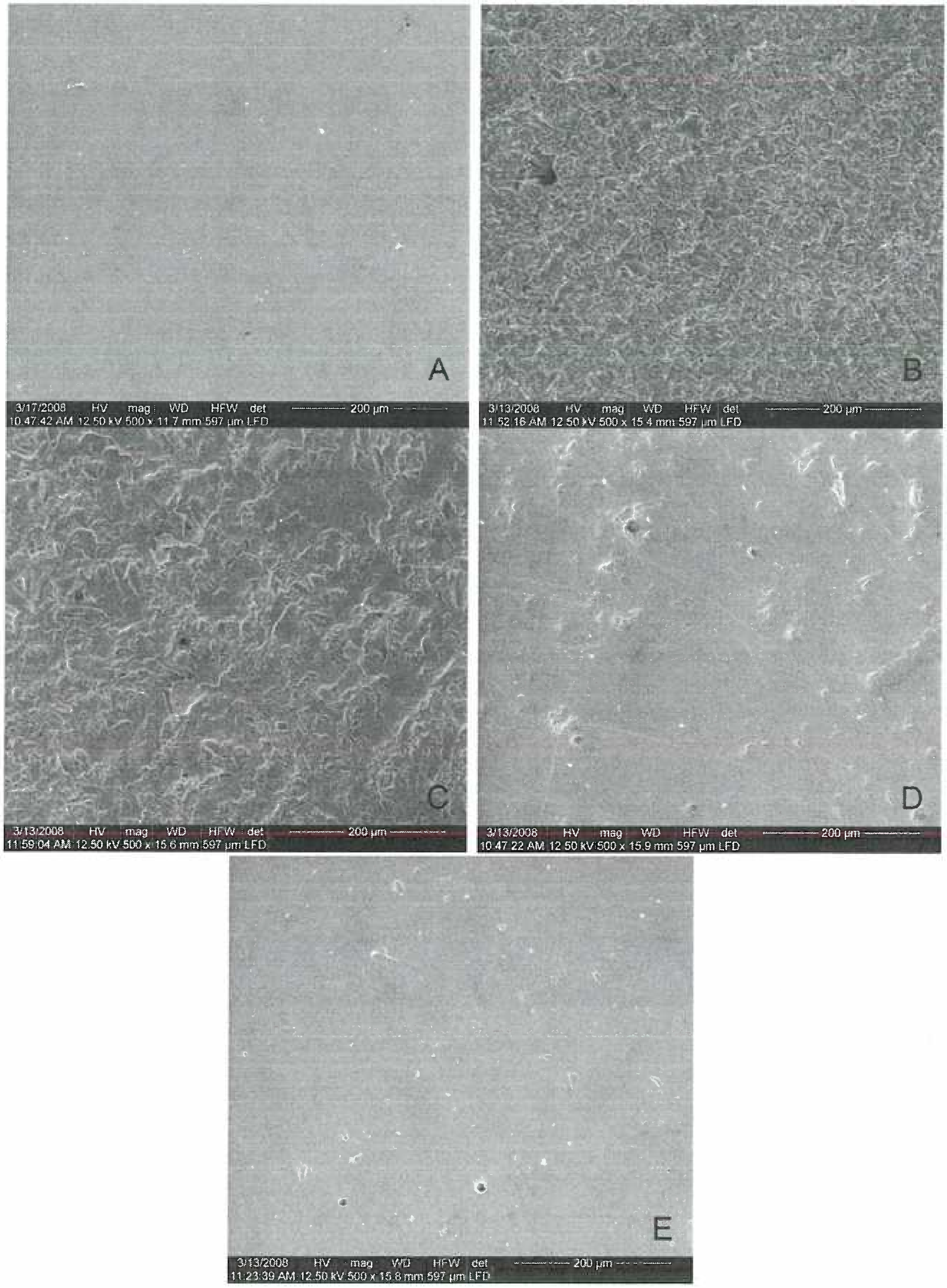

Figure 4. SEM images (500x) from the sandblasting, hydrofluoric acid etching, and silane bonding method group. (A) Autoglazed control. (B) After SB+HF but prior to bracket bonding. (C) After bracket debond and residual resin removal with the finishing bur. (D) After polishing with the porcelain polishing kit. (E) After polishing with the diamond polishing paste.

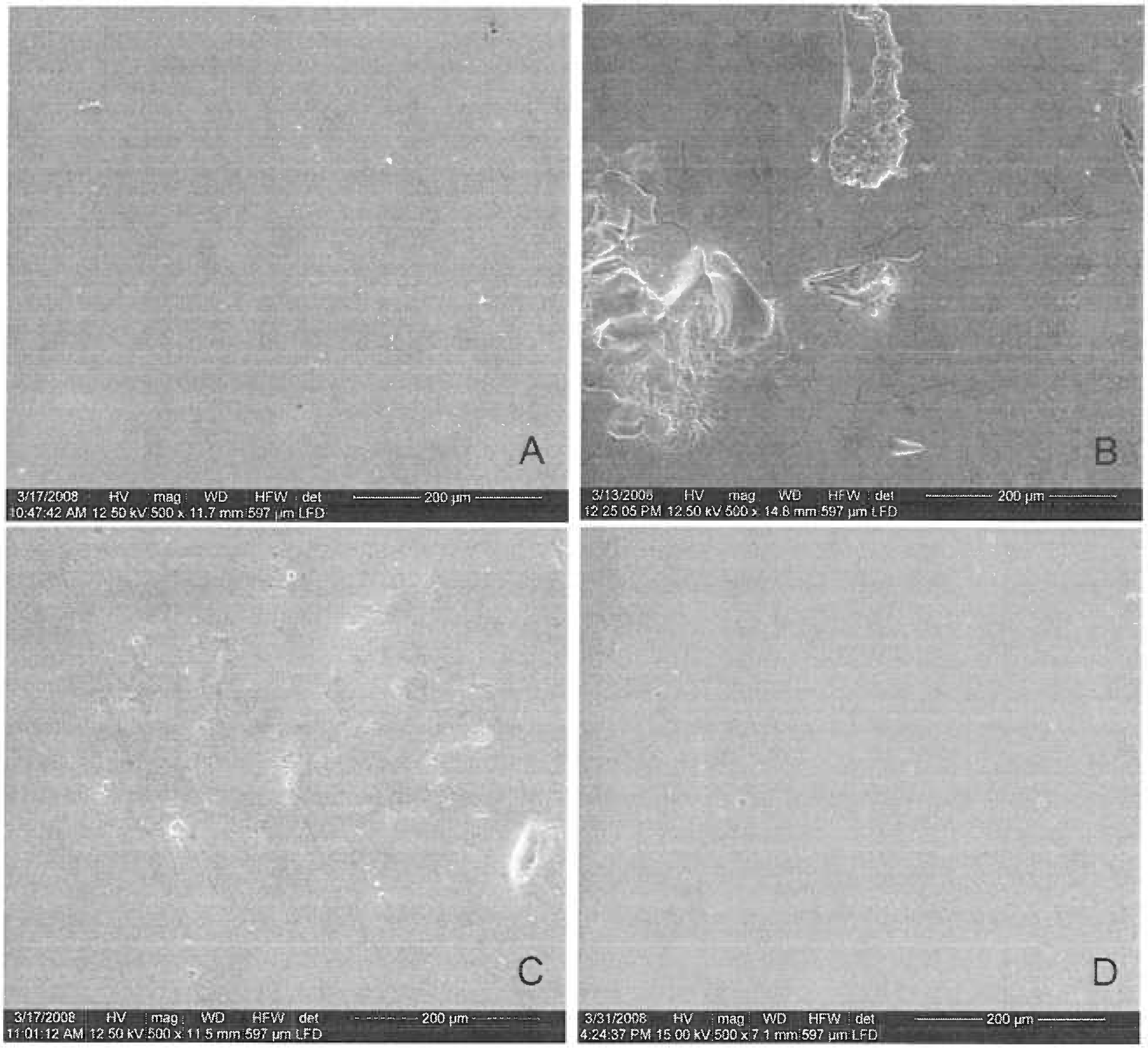

Figure 5. SEM images (500x) from the phosphoric acid and silane bonding method group. (A) Autoglazed control. (B) After bracket debond and residual resin removal with the finishing bur. (C) After polishing with the porcelain polishing kit. (D) After polishing with the diamond polishing paste.

REFERENCES

1. Ajlouni R, Bishara SE, Oonsombat C, Soliman M, Laffoon J. The effect of porcelain surface conditioning on bonding orthodontic brackets. Angle Orthod. 2005 Sep;75(5):858-64.

2. Akova T, Yoldas O, Toroglu MS, Uysal H. Porcelain surface treatment by laser for bracket-porcelain bonding. Am J Orthod Dentofacial Orthop. 2005 Nov;128(5):630-7.

3. Bourke BM, Rock WP. Factors affecting the shear bond strength of orthodontic brackets to porcelain. Br J Orthod. 1999 Dec;26(4):285-90.

4. Campbell SD. Evaluation of surface roughness and polishing techniques for new ceramic materials. J Prosthet Dent. 1989 May;61(5):563-8.

5. Cochran D, O'Keefe KL, Turner DT, Powers JM. Bond strength of orthodontic composite cement to treated porcelain. Am J Orthod Dentofacial Orthop. 1997 Mar;111(3):297-300.

6. Commission Internationale l'Eclairage. Colorimetry. CIE Publication No. 15.2. 1986:74.

7. Dahlberg G. Statistical methods for medical and biological students. New York: Interscience Publications; 1940.

8. de Jager N, Feilzer AJ, Davidson CL. The influence of surface roughness on porcelain strength. Dent Mater. 2000 Nov;16(6):381-8.

9. Eustaquio R, Garner LD, Moore BK. Comparative tensile strengths of brackets bonded to porcelain with orthodontic adhesive and porcelain repair systems. Am J Orthod Dentofacial Orthop. 1988 Nov;94(5):421-5.

10. Ferri NP, Eliades T, Zinelis S, Bradley TG. Force to debond brackets from high-fusing and low-fusing porcelain systems. Angle Orthod. 2006 Mar;76(2):278-81.

11. Fischer H, Schafer M, Marx R. Effect of surface roughness on flexural strength of veneer ceramics. J Dent Res. 2003 Dec;82(12):972-5.

12. Gillis I, Redlich M. The effect of different porcelain conditioning techniques on shear bond strength of stainless steel brackets. Am J Orthod Dentofacial Orthop. 1998 Oct;114(4):387-92.

13. Harari D, Shapira-Davis S, Gillis I, Roman I, Redlich M. Tensile bond strength of ceramic brackets bonded to porcelain facets. Am J Orthod Dentofacial Orthop. 2003 May;123(5):551-4.

14. Henderson T. The physics classroom tutorial, lesson 1: Reflection and its importance [web page on the Internet]. 2007 [cited August 2008]. Available from: http://www.glenbrook.k12.il.us/gbssci/phys/class/refln/reflntoc.html.

15. Houston WJ. The analysis of errors in orthodontic measurements. Am J Orthod. 1983 May;83(5):382-90.

16. Jarvis J, Zinelis S, Eliades T, Bradley TG. Porcelain surface roughness, color and gloss changes after orthodontic bonding. Angle Orthod. 2006 Mar;76(2):274-7.

17. Karan S, Buyukyilmaz T, Toroglu MS. Orthodontic bonding to several ceramic surfaces: Are there acceptable alternatives to conventional methods? Am J Orthod Dentofacial Orthop. 2007 Aug;132(2):144.e7,144.14.

18. Karan S, Toroglu MS. Porcelain refinishing with two different polishing systems after orthodontic debonding. Angle Orthod. 2008 Sep;78(5):947-53.

19. Kawai K, Urano M, Ebisu S. Effect of surface roughness of porcelain on adhesion of bacteria and their synthesizing glucans. J Prosthet Dent. 2000 Jun;83(6):664-7.

20. Larmour CJ, Bateman G, Stirrups DR. An investigation into the bonding of orthodontic attachments to porcelain. Eur J Orthod. 2006 Feb;28(1):74-7.

21. Leinfelder KF. Porcelain esthetics for the 21st century. J Am Dent Assoc. 2000 Jun;131 Suppl:47S-51S.

22. Nebbe B, Stein E. Orthodontic brackets bonded to glazed and deglazed porcelain surfaces. Am J Orthod Dentofacial Orthop. 1996 Apr;109(4):431-6.

23. Pannes DD, Bailey DK, Thompson JY, Pietz DM. Orthodontic bonding to porcelain: A comparison of bonding systems. J Prosthet Dent. 2003 Jan;89(1):66-9.

24. Patterson CJ, McLundie AC, Stirrups DR, Taylor WG. Refinishing of porcelain by using a refinishing kit. J Prosthet Dent. 1991 Mar;65(3):383-8.

25. Patterson CJ, McLundie AC, Stirrups DR, Taylor WG. Efficacy of a porcelain refinishing system in restoring surface finish after grinding with fine and extra-fine diamond burs. J Prosthet Dent. 1992 Sep;68(3):402-6.

26. Powers JM. Optical properties. In: Restorative Dental Materials. Craig RG, Powers JM, editors. 11th ed. St. Louis: Mosby; 2002. p. 38-47.

27. Reynolds IR. A review of orthodontic bonding. Br J Orthod. 1975;2:171-8.

28. Sarac D, Sarac YS, Yuzbasioglu E, Bal S. The effects of porcelain polishing systems on the color and surface texture of feldspathic porcelain. J Prosthet Dent. 2006 Aug;96(2):122-8.

29. Sarac YS, Elekdag-Turk S, Sarac D, Turk T. Surface conditioning methods and polishing techniques effect on surface roughness of a feldspar ceramic. Angle Orthod. 2007 Jul;77(4):723-8.

30. Schmage P, Nergiz I, Herrmann W, Ozcan M. Influence of various surface-conditioning methods on the bond strength of metal brackets to ceramic surfaces. Am J Orthod Dentofacial Orthop. 2003 May;123(5):540-6.

31. Scurria MS, Powers JM. Surface roughness of two polished ceramic materials. J Prosthet Dent. 1994 Feb;71(2):174-7.

32. Shackleford JF. Ceramics and glasses: Major optical properties. In: Introduction to Materials Science for Engineers. 3rd ed. New York: Macmillan; 1992. p. 413-23.

33. Smith GA, McInnes-Ledoux P, Ledoux WR, Weinberg R. Orthodontic bonding to porcelain--bond strength and refinishing. Am J Orthod Dentofacial Orthop. 1988 Sep;94(3):245-52.

34. Tanaka T, Kunishi T, Wakeshima H. Relation between gloss and wetting of a matte surface. Optics Letters. 1985 April;10(4):170-2.

35. Turk T, Sarac D, Sarac YS, Elekdag-Turk S. Effects of surface conditioning on bond strength of metal brackets to all-ceramic surfaces. Eur J Orthod. 2006 Oct;28(5):450-6.

36. Turkkahraman H, Kucukesmen HC. Porcelain surface-conditioning techniques and the shear bond strength of ceramic brackets. Eur J Orthod. 2006 Oct;28(5):440-3.

37. Whitlock BO,3rd, Eick JD, Ackerman RJ,Jr, Glaros AG, Chappell RP. Shear strength of ceramic brackets bonded to porcelain. Am J Orthod Dentofacial Orthop. 1994 Oct;106(4):358-64.

38. Wolf DM, Powers JM, O'Keefe KL. Bond strength of composite to etched and sandblasted porcelain. Am J Dent. 1993 Jun;6(3):155-8.

39. Wood DP, Jordan RE, Way DC, Galil KA. Bonding to porcelain and gold. Am J Orthod. 1986 Mar;89(3):194-205.

40. Wright MD, Masri R, Driscoll CF, Romberg E, Thompson GA, Runyan DA. Comparison of three systems for the polishing of an ultra-low fusing dental porcelain. J Prosthet Dent. 2004 Nov;92(5):486-90.

41. Zachrisson BU. Orthodontic bonding to artificial tooth surfaces: Clinical versus laboratory findings. Am J Orthod Dentofacial Orthop. 2000 May;117(5):592-4.

42. Zachrisson BU. Bonding in orthodontics. In: Orthodontics: current principles and techniques. Graber TM, Vanarsdall RL, Vig KWL, editors. 4th ed. St. Louis: Elsevier Mosby; 2005. p. 579-659.

43. Zachrisson YO, Zachrisson BU, Buyukyilmaz T. Surface preparation for orthodontic bonding to porcelain. Am J Orthod Dentofacial Orthop. 1996 Apr;109(4):420-30.

44. Zelos L, Bevis RR, Keenan KM. Evaluation of the ceramic/ceramic interface. Am J Orthod Dentofacial Orthop. 1994 Jul;106(1):10-21.

Appendix 1. Bond strengths of orthodontic brackets to porcelain. Selected studies are listed.
Surface treatments key: G = glazed, D = deglazed, HF = hydrofluoric acid, PA = phosphoric acid, S = silane.

Authors	Surface Treatment	Adhesive	Porcelain Type	Thermo-cycled	Mean Bond Strength, Shear/Tensile (MPa)	Std. Dev. (MPa)
Smith et al. (1988)	G+S	Composite, (Concise, 3M, St. Paul, MN)	Feldspathic (Vita Zahnfabrik Rauter, Bad Sackingen, Germany)	Yes	11.1 (Shear)	3.9
	D+S (green stone)				8.1 (Shear)	2.2
	D (green stone)				2.1 (Shear)	1.4
Eustaquio et al. (1988)	G+S	Composite, (System 1+, Ormco, Glendora, CA)	Feldspathic Ceramco II (Ceramco, Inc., East Windsor, NJ)	Yes	6.58 (Tensile)	0.78
	D+S (green stone)				5.77 (Tensile)	0.91
Whitlock et al. (1994)	G+PA+S	Composite, (Concise, 3M, St. Paul, MN)	Feldspathic Ceramco II (Ceramco, Inc. Burlington, NJ)	No	6.5 (Shear)	0.8
	G+PA				3.8 (Shear)	0.4
Zelos et al. (1994)	G+S (Scotchprime, 3M, MN)	Composite, (Transbond, 3M, St. Paul, MN)	Feldspathic Ceramco (Ceramco, Inc. Burlington, NJ)	Yes	11.75 (Shear)	2.52
					6.68 (Tensile)	1.34
	G+S (Porcelain Primer, Ormco, Glendora, CA)	Composite, (Concise, 3M, St. Paul, MN)			15.24 (Shear)	1.75
					6.22 (Tensile)	1.06
Nebbe et al. (1996)	G+PA+S	Composite, (Transbond, 3M, St. Paul, MN)	Feldspathic (Vivadent, Degussa Corp., Liechtenstein)	No	19.36 (Shear)	4.52
	D+PA+S (brown stone)				15.80 (Shear)	1.88
Zachrisson et al. (1996)	D+S (sandblasting)	Composite (Concise, 3M, St. Paul, MN)	Feldspathic Biodent (DeTrey/Dentsply, Dreieich, Germany)	Yes	11.6 (Tensile)	2.9
	D+HF (sandblasting)				11.5 (Tensile)	2.8
	D (sandblasting)				2.5 (Tensile)	0.7
Gillis and Redlich (1998)	G+HF+S	Composite (Concise, 3M, St. Paul, MN)	Feldspathic Ceramco II (Ceramco Inc., Burlington, NJ)	No	16.24 (Shear)	3.55
	D+S (sandblast)				17.90 (Shear)	3.65
	D+S (coarse diamond)				12.20 (Shear)	4.85

Authors	Surface Treatment	Adhesive	Porcelain Type	Thermo-cycled	Mean Bond Strength, Shear/Tensile (MPa)	Std. Dev. (MPa)
Bourke and Rock (1999)	G	Composite (Scotchbond, 3M, St. Paul, MN)	Feldspathic	Yes	0 (Shear)	0
	G+PA			Yes	0 (Shear)	0
	G+HF			Yes	3.52 (Shear)	0.24
	G+S			Yes	8.42 (Shear)	2.59
	G+PA+S			Yes	10.04 (Shear)	2.84
	G+HF+S			Yes	10.29 (Shear)	1.30
	D (sandblast)			Yes	1.47 (Shear)	0.47
	D+PA (sandblast)			Yes	3.07 (Shear)	0.57
	D+HF (sandblast)			Yes	6.16 (Shear)	1.42
	D+S (sandblast)			Yes	8.06 (Shear)	1.84
	D+PA+S (sandblast)			Yes	8.52 (Shear)	1.03
	D+HF+S (sandblast)			Yes	9.53 (Shear)	1.48
	D+HF+S (sandblast)			No	18.69 (Shear)	1.40
Harari et al. (2003)	G+HF+S	Composite (Right-On, TP Orthodontics, La Porte, IN)	Feldspathic Ceramco II (Ceramco, Inc. Burlington, NJ)	No	7.1 (Tensile)	2.6
	D+S (sandblast)				3.8 (Tensile)	2.4
	G+HF	Composite containing silane coupling agents (Ideal 1, BJM, Or-Yehuda, Israel)			7.7 (Tensile)	3.0
	D (sandblast)				4.1 (Tensile)	2.3
Pannes et al. (2003)	G+PA+S	Composite (Transbond, 3M Unitek, Puchheim, Germany)	Feldspathic (Vita Omega, Vita, Bad Sackingen, Germany)	No	7.64 (Shear)	N/A
	G+PA+S	Composite (Spectrum, American Orthodontic, Sheboygan, WI)			8.09 (Shear)	N/A
	G+PA+S	Resin Modified Glass Ionomer (Fuji Ortho LC, GC Germany, Maintal-Dornigheim, Germany)			8.73 (Shear)	N/A
Schmage et al. (2003)	G	Composite (Concise, 3M, St. Paul, MN)	Feldspathic (VMK68, Vita, Bad Sackingen, Germany)	Yes	0 (Shear)	0
	D (diamond bur)				1.6 (Shear)	0.8
	D (sandblast)				2.8 (Shear)	1.5
	D+S (sandblast)				15.8 (Shear)	4.2
	G+HF				14.7 (Shear)	3.3
	G+HF+S				12.2 (Shear)	3.4
	D+S (silicazation)				14.9 (Shear)	3.8

Authors	Surface Treatment	Adhesive	Porcelain Type	Thermo-cycled	Mean Bond Strength, Shear/Tensile (MPa)	Std. Dev. (MPa)
Ajlouni et al. (2005)	G+PA	Composite (Transbond XT, 3M Unitek, Monrovia, CA)	Feldspathic Denture Teeth (Solerex Trubyte, Dentsply, York, PA)	No	4.4 (Shear)	2.7
	G+PA+S				10.3 (Shear)	5.3
	D+HF+S (sandblast)				11.2 (Shear)	4.7
Larmour et al. (2006)	G+PA+S	Composite, (Transbond, 3M Unitek, St. Paul, MN)	Feldspathic Denture Teeth (Ivoclar-Vivadent, Leicester, UK)	No	7.9 (Shear)	N/A
	G+HF+S				9.7 (Shear)	N/A
	G+PA+S	Resin Modified Glass Ionomer (Fuji Ortho LC, GC Corp., Tokyo, Japan)			1.8 (Shear)	N/A
	G+HF+S				6.3 (Shear)	N/A
Türk et al. (2006)	D+S (sandblast)	Composite (Transbond XT, 3M Unitek, Monrovia, CA)	Feldspathic (Vitadur Alpha, Vita, Bad Sackingen, Germany)	Yes	14.66 (Shear)	3.17
	D+S (fine diamond)				26.38 (Shear)	4.96
	G+HF+S				5.39 (Shear)	2.59
	D+S (sandblast)		Lithium Disilicate (Empress 2, Ivoclar-Vivadent, Schaan, Liechtenstein)		26.15 (Shear)	6.70
	D+S (fine diamond)				28.20 (Shear)	3.63
	G+HF+S				11.11 (Shear)	4.07
Türkkahraman, Küçükeşmen (2006)	G+HF+S	Composite (Light Bond, Reliance Ortho. Products, Itasca, IL)	Feldspathic (Vita Zahnfabrik, Bad Sackingen, Germany)	Yes	11.38 (Shear)	1.65
	D+HF+S (sandblast)				10.45 (Shear)	1.15
	D+S (sandblast)				5.46 (Shear)	1.34
Saraç et al. (2007)	D+S (sandblast)	Composite (Transbond XT, 3M Unitek, Monrovia, CA)	Feldspathic (Vitadur Alpha, Vita, Bad Sackingen, Germany)	Yes	17.90 (Shear)	3.22
	G+HF+S				5.39 (Shear)	2.59
	D+HF+S (sandblast)				20.37 (Shear)	3.02

Authors	Surface Treatment	Adhesive	Porcelain Type	Thermo-cycled	Mean Bond Strength, Shear/Tensile (MPa)	Std. Dev. (MPa)
Karan et al. (2007)	D (sandblast)	Composite (Transbond XT, 3M Unitek, Monrovia, CA)	Feldspathic (IPS d.sign, Ivoclar-Vivadent, Schaan, Liechtenstein)	Yes	3.2 (Shear)	2.7
	D+HF (sandblast)				11.3 (Shear)	4.1
	D+HF+S (sandblast)				10.5 (Shear)	6.0
	D+S (sandblast)				10.7 (Shear)	5.1
	D+S (silicazation)				15.2 (Shear)	5.9
	D (sandblast)	Composite (Transbond XT, 3M Unitek, Monrovia, CA)	Leucite-based (IPS Empress, Ivoclar-Vivadent, Schaan, Liechtenstein)	Yes	3.9 (Shear)	3.0
	D+HF (sandblast)				14.7 (Shear)	5.8
	D+HF+S (sandblast)				9.9 (Shear)	5.0
	D+S (sandblast)				12.3 (Shear)	8.5
	D+S (silicazation)				13.4 (Shear)	6.5
	D (sandblast)	Composite (Transbond XT, 3M Unitek, Monrovia, CA)	Lithia disilicate-based (IPS Empress 2, Ivoclar-Vivadent, Schaan, Liechtenstein)	Yes	3.1 (Shear)	2.6
	D+HF (sandblast)				8.6 (Shear)	4.8
	D+HF+S (sandblast)				5.7 (Shear)	3.6
	D+S (sandblast)				11.8 (Shear)	6.1
	D+S (silicazation)				13.2 (Shear)	7.7

Appendix 2. Refinishing porcelain surfaces following orthodontic bracket debonding with a testing machine. Selected studies are listed. Mean Surface Roughness = Ra. Gloss is the percentage of incident beam vs. refracted beam. Color data is the percentage of specimens exhibiting color changes after debonding and polishing. Surface treatments key: G = glazed, D = deglazed, HF = hydrofluoric acid, S = silane.

Authors	Bracket to Porcelain Bonding Method	Porcelain Type	Porcelain Polishing Stage	Ra, µm, (SD)	Gloss (SD)	Color (%)
Jarvis et al. (2006)	D+HF+S, porcelain was not glazed but polished prior to bonding with the Dialite system (Brassler, Savannah, GA) Composite (Transbond XT, 3M Unitek, Monrovia, CA)	Feldspathic, high fusing, (Vitadur Alpha, Vident, Brea, CA)	Pre-bond (control) porcelain was polished but not glazed	0.38 (0.13)	7.8 (5.9)	
			Post-bond, 12-fluted carbide bur (Brassler, Savannah, GA)	1.48 (0.65)	2.8 (1.8)	70 (shade) 40 (value) 40 (hue)
			Post-bond, Bur plus Sof-Lex polishing discs, (3M Unitek, Monrovia, CA)	1.15 (0.82)	11.9 (5.4)	30 (shade) 20 (value) 60 (hue)
		Feldspathic, low fusing, (Vita Omega 900, Vident, Brea, CA)	Pre-bond (control) measurements, porcelain was polished but not glazed	0.45 (0.16)	22.2 (9.3)	
			Post-bond, 12-fluted carbide bur	1.44 (0.74)	16.8 (8.1)	50 (shade) 60 (value) 90 (hue)
			Post-bond, Bur plus Sof-Flex polishing discs	0.97 (0.78)	25.5 (9.6)	10 (shade) 20 (value) 60 (hue)
Saraç et al. (2007)	D+S (sandblast) Composite (Transbond XT)	Feldspathic (Vitadur Alpha, Vita, Bad Sackingen, Germany)	Post-bond measurements, prior to polishing (no pre-bond Ra data recorded)	3.90 (0.27)	Not tested	Not tested
			Porcelain adjustment kit (Shofu, Ratingen, Germany)	2.02 (0.24)		
			Polishing paste, (Diamond Stick, Shofu, Ratingen, Germany)	3.71 (0.10)		
			Porcelain adjustment kit and polishing paste	2.48 (0.24)		
	G+HF+S Composite (Transbond XT)		Post-bond measurements, prior to polishing	2.22 (0.13)		
			Porcelain adjustment kit	1.65 (0.13)		
			Polishing paste	1.89 (0.09)		
			Porcelain adjustment kit and polishing paste	1.47 (0.18)		
	D+HF+S (sandblast) Composite (Transbond XT)		Post-bond measurements, prior to polishing	4.02 (0.30)		
			Porcelain adjustment kit	1.83 (0.22)		
			Polishing paste	3.81 (0.14)		
			Porcelain adjustment kit and polishing paste	1.32 (0.17)		

Authors	Bracket to Porcelain Bonding Method	Porcelain Type	Porcelain Polishing Stage	Ra, µm, (SD)	Gloss (SD)	Color (% change)
Karan and Toroglu (2008)	D+HF+S (sandblast) Composite (Transbond XT, 3M Unitek, Monrovia, CA)	Feldspathic (IPS d.sign, Ivoclar-Vivadent, Schaan, Liechtenstein)	Pre-bond (control) measurements of glazed porcelain	0.0048 (0.0006)	Not tested	Not tested
			Post-bond, 12-fluted carbide bur followed by: Polishing wheel (Cera Master, Shofu, Menlo Park, CA) and polishing paste (Ultra II, Shofu)	0.1665 (0.0392)		
			Post-bond, 12-fluted carbide bur followed by: Sof-Lex polishing discs, (3M ESPE, Seefeld, Germany)	0.1025 (0.0398)		
		Leucite-based (IPS Empress, Ivoclar-Vivadent, Schaan, Liechtenstein)	Pre-bond (control) measurements of glazed porcelain	0.0039 (0.0009)		
			Post-bond, 12-fluted carbide bur followed by: Polishing wheel and polishing paste	0.1504 (0.0419)		
			Post-bond, 12-fluted carbide bur followed by: Sof-Lex polishing discs	0.0721 (0.0305)		
		Lithia disilicate-based (IPS Empress 2, Ivoclar-Vivadent, Schaan, Liechtenstein)	Pre-bond (control) measurements of glazed porcelain	0.0027 (0.0012)		
			Post-bond, 12-fluted carbide bur followed by: Polishing wheel and polishing paste	0.1924 (0.0376)		
			Post-bond, 12-fluted carbide bur followed by: Sof-Lex polishing discs	0.0582 (0.0305)		

Appendix 3: Refinishing porcelain surfaces abraded with a diamond bur. Selected studies are listed. In the first study, surface roughness (Ra) is shown as the mean difference, ΔRa = Ra(glazed control) – Ra(polished). A positive value indicates the polished specimen was smoother than the glazed control. In the second study, mean surface roughness values and mean color change (ΔE) from the control are shown.

Authors	Porcelain Abrasion Method	Porcelain Type	Porcelain Polishing System	ΔRa, μm, (SD)	Color (ΔE)
Wright et al. (2004)	Medium-grit diamond bur (size 016, no. 848-11, Brasseler, Savannah, GA)	Feldspathic, ultra-low fusing, (Finesse, Dentsply Ceramco, Burlington, NJ)	Axis Dental polishing system (Axis Dental, Irvington, TX)	0.586 (0.256)	Not tested
			Jelenko polishing system (Heraeus Kulzer, Armonk, NY)	0.306 (0.238)	
			Brasseler polishing system (Brasseler, Savannah, GA)	0.277 (0.230)	
Sarac et al. (2006)	Medium-grit diamond bur (Diatech Dental, Heerbrugg, Switzerland)	Feldspathic, (Vitadur Alpha, Vita, Bad Sackingen, Germany)	Glazed porcelain (control)	1.58 (0.12)	
			Porcelain adjustment kit (Shofu Dental, Ratingen, Germany)	1.62 (0.15)	1.20 (0.09)
			Polishing wheel (Cera Master, Shofu Dental)	2.23 (0.12)	1.49 (0.13)
			Polishing stick (Diamond Stick, Shofu Dental)	3.08 (0.15)	3.38 (0.18)
			Polishing paste (Ultra II, Shofu Dental)	2.96 (0.15)	2.98 (0.12)
			Porcelain adjustment kit and polishing stick	1.46 (0.10)	1.11 (0.11)
			Porcelain adjustment kit and polishing paste	1.46 (0.13)	1.07 (0.11)
			Polishing wheel and polishing stick	1.99 (0.13)	1.56 (0.13)
			Polishing wheel and polishing paste	1.96 (0.13)	1.47 (0.13)

Appendix 4.

Control Data 9/17/2007

Prior to Bonding

Surface Roughness **Ra (µm)**
Cut off = 0.25mm n*Cut off (Length) = 5*0.25 = 1.25mm
Std = ISO Range = +/-80 micrometers

<u>SB+HF+S</u>

Sample				Mean
1	0.093	0.316	0.204	0.204
2	0.083	0.082	0.101	0.089
3	0.171	0.272	0.156	0.200
4	0.071	0.231	0.328	0.210
5	0.141	0.152	0.205	0.166
6	0.148	0.146	0.170	0.155
7	0.150	0.091	0.075	0.105
8	0.189	0.112	0.123	0.141
9	0.098	0.151	0.278	0.176
10	0.167	0.068	0.115	0.117
11	0.180	0.218	0.165	0.188
12	0.097	0.134	0.079	0.103
13	0.102	0.037	0.082	0.074
14	0.261	0.198	0.189	0.216
15	0.180	0.161	0.272	0.204
16	0.290	0.255	0.203	0.249
17	0.181	0.142	0.163	0.162
18	0.056	0.129	0.271	0.152
19	0.108	0.197	0.066	0.124
20	0.128	0.122	0.217	0.156
			Mean	0.160
			Std. Dev.	0.047

<u>PA+S</u>

Sample				Mean
21	0.185	0.108	0.104	0.132
22	0.131	0.118	0.083	0.111
23	0.082	0.078	0.107	0.089
24	0.116	0.104	0.151	0.124
25	0.298	0.230	0.318	0.282
26	0.169	0.293	0.213	0.225
27	0.192	0.296	0.326	0.271
28	0.151	0.161	0.202	0.171
29	0.225	0.213	0.121	0.186
30	0.123	0.174	0.1	0.132
31	0.126	0.168	0.111	0.135
32	0.126	0.137	0.135	0.133
33	0.209	0.119	0.314	0.214
34	0.091	0.056	0.163	0.103
35	0.147	0.285	0.259	0.230
36	0.145	0.125	0.11	0.127
37			fracture	
38	0.338	0.32	0.245	0.301
39	0.115	0.161	0.157	0.144
40	0.172	0.167	0.191	0.177
			Mean	0.173
			Std. Dev.	0.064

Control Data 9/17/2007

Prior to Bonding

Gloss (% of incident light beam that is reflected)

SB+HF+S

Sample	Gloss
1	39.2
2	50.8
3	38.1
4	53.4
5	35.6
6	38.0
7	35.0
8	39.4
9	40.7
10	42.2
11	32.2
12	33.6
13	44.3
14	56.2
15	35.0
16	38.2
17	43.3
18	35.2
19	44.4
20	52.0
Mean	41.3
Std. Dev.	7.0

PA+S

Sample	Gloss
21	50.9
22	35.9
23	43.2
24	49.5
25	34.4
26	39.5
27	51.5
28	32.6
29	51.2
30	48.9
31	35.8
32	49.9
33	31.9
34	42.2
35	33.7
36	39.3
37	fracture
38	33.3
39	38.4
40	50.1
Mean	41.7
Std. Dev.	7.4

Control Data 9/19/2007

Prior to Bonding

Color (L, a, b)

SB+HF+S

Sample	L	a	b
1	65.13	0.30	16.24
2	65.18	0.33	15.48
3	68.24	0.83	16.67
4	65.02	0.50	16.48
5	65.53	0.13	16.39
6	65.41	0.39	16.58
7	64.34	0.60	15.96
8	64.71	0.35	15.55
9	64.89	0.26	15.19
10	64.99	0.37	16.09
11	65.46	0.21	16.07
12	65.34	0.57	16.35
13	65.20	0.34	15.89
14	64.35	0.36	16.03
15	65.46	0.10	15.43
16	65.20	0.14	16.31
17	64.49	0.64	15.68
18	63.79	0.35	16.02
19	64.32	0.36	15.12
20	65.37	0.16	16.12
Mean	65.12	0.36	15.98
Std. Dev.	0.88	0.19	0.45

PA+S

Sample	L	a	b
21	64.82	0.38	16.11
22	63.75	0.31	15.34
23	65.56	0.49	15.99
24	64.70	0.13	15.49
25	64.73	0.13	15.86
26	64.38	0.06	15.21
27	64.71	0.06	16.00
28	64.99	0.11	15.48
29	65.27	0.21	15.89
30	64.15	0.20	15.27
31	63.80	0.28	15.53
32	65.44	0.47	15.93
33	64.52	0.23	15.77
34	64.61	0.28	15.52
35	65.30	0.22	16.01
36	64.19	0.14	15.37
37		fracture	
38	64.34	0.06	15.93
39	64.84	0.15	15.42
40	64.07	0.32	16.07
Mean	64.64	0.22	15.69
Std. Dev.	0.53	0.13	0.30

Debond/Bur Data 10/24/2007 10/30/2007 11/5/2007

After debond and initial resin clean-up with a 12-fluted carbide bur

Surface Roughness	**Ra (μm)**
Cut off = 0.25mm	n*Cut off (Length) = 5*0.25 = 1.25mm
Std = ISO	Range = +/-80 micrometers

<u>SB+HF+S</u> <u>PA+S</u>

Sample				Mean	Sample				Mean
1	0.878	1.245	1.150	1.091	21	0.243	0.355	0.326	0.308
2	0.647	0.637	0.717	0.667	22	0.304	0.267	0.308	0.293
3	0.981	0.720	1.148	0.950	23	0.270	0.299	0.643	0.404
4	0.755	0.792	0.665	0.737	24	0.148	0.482	0.458	0.363
5	0.786	0.689	0.857	0.777	25	0.362	0.315	0.330	0.336
6	1.673	1.204	1.220	1.366	26	0.254	0.204	0.188	0.215
7	0.870	1.028	1.171	1.023	27	0.397	0.278	0.192	0.289
8	1.820	1.517	1.018	1.452	28	0.356	0.437	0.512	0.435
9	0.923	1.086	1.261	1.090	29	0.249	0.258	0.687	0.398
10	1.355	1.271	1.099	1.242	30	0.187	0.126	0.103	0.139
11	1.313	1.348	1.251	1.304	31	0.241	0.382	0.843	0.489
12	0.736	0.935	1.130	0.934	32	0.134	0.229	0.212	0.192
13	1.089	1.369	1.263	1.240	33	0.165	0.329	0.247	0.247
14	1.098	0.924	0.835	0.952	34	0.403	0.498	0.227	0.376
15	1.615	1.523	1.743	1.627	35	0.327	0.217	0.469	0.338
16	0.699	0.826	0.867	0.797	36	0.291	0.230	0.226	0.249
17	1.113	1.146	0.901	1.053	37			fracture	
18	1.208	1.615	1.707	1.510	38	0.288	0.312	0.383	0.328
19	1.534	1.208	1.026	1.256	39	0.604	0.750	0.566	0.640
20	1.303	1.361	1.391	1.352	40	0.316	0.567	0.419	0.434
			Mean	1.121				Mean	0.341
			Std. Dev.	0.271				Std. Dev.	0.116

Measurement error, re-test 5 random samples

17	1.400	1.156	1.072	1.209	29	0.470	0.296	0.311	0.359
5	0.800	0.817	1.145	0.921	40	0.443	0.298	0.450	0.397
9	0.795	0.815	1.110	0.907	30	0.070	0.162	0.148	0.127
1	1.295	1.080	0.924	1.100	33	0.409	0.264	0.344	0.339
13	1.313	1.511	1.226	1.350	27	0.263	0.253	0.306	0.274
			Mean	1.097				Mean	0.299
			Std. Dev.	0.190				Std. Dev.	0.106

Debond/Bur Data 10/17/2007 10/18/2007

After debond and initial resin clean-up with a 12-fluted carbide bur

Gloss (% of incident light beam that is reflected)

SB+HF+S

Sample	Gloss
1	2.0
2	2.6
3	2.8
4	6.8
5	2.4
6	2.9
7	1.9
8	7.1
9	2.0
10	3.0
11	6.4
12	7.3
13	2.2
14	2.5
15	2.4
16	2.3
17	3.3
18	4.3
19	7.2
20	2.0
Mean	3.7
Std. Dev.	2.0

PA+S

Sample	Gloss
21	43.3
22	25.7
23	30.7
24	40.3
25	32.3
26	36.4
27	51.9
28	27.8
29	50.4
30	47.4
31	30.5
32	33.7
33	30.5
34	30.3
35	37.6
36	35.1
37	fracture
38	41.6
39	42.1
40	54.3
Mean	38.0
Std. Dev.	8.5

Measurement error, re-test 5 random samples

11	6.0
13	1.8
20	2.3
2	5.5
5	1.9
Mean	3.5
Std. Dev.	2.1

22	30.6
38	41.4
33	34.6
39	25.7
26	28.8
Mean	32.2
Std. Dev.	6.1

Debond/Bur Data 10/18/2007 10/24/2007

After debond and initial resin clean-up with a 12-fluted carbide bur

Color (L, a, b)

SB+HF+S

Sample	L	a	b
1	68.07	0.13	13.35
2	68.02	0.22	13.10
3	70.76	0.46	13.62
4	68.12	0.06	13.56
5	68.22	-0.07	14.10
6	68.62	0.04	13.32
7	68.58	0.08	11.99
8	67.43	0.14	12.38
9	68.78	0.03	11.67
10	68.29	0.01	12.98
11	66.80	-0.25	12.15
12	67.83	0.07	13.49
13	67.99	-0.01	12.79
14	67.40	-0.01	12.89
15	67.65	0.23	12.87
16	68.55	0.26	13.02
17	67.87	0.52	11.74
18	67.31	0.45	12.18
19	67.20	0.48	12.35
20	68.22	0.32	12.96
Mean	68.09	0.16	12.83
Std. Dev.	0.82	0.21	0.67

PA+S

Sample	L	a	b
21	65.03	0.37	15.70
22	63.97	0.29	15.25
23	66.78	0.33	15.32
24	65.13	0.36	14.46
25	64.85	0.26	15.59
26	64.59	0.04	15.08
27	64.54	0.14	16.00
28	65.20	0.10	15.42
29	65.51	0.21	15.78
30	64.08	0.25	15.29
31	63.91	0.47	15.01
32	65.60	0.37	15.81
33	64.58	0.26	15.46
34	64.84	0.39	15.25
35	66.00	0.32	15.30
36	64.70	0.23	15.12
37		fracture	
38	65.27	0.16	14.98
39	64.94	0.23	15.09
40	64.10	0.43	16.12
Mean	64.93	0.27	15.37
Std. Dev.	0.72	0.11	0.40

Measurement error, re-test 5 random samples

Sample	L	a	b
8	67.38	0.41	12.30
1	67.82	0.16	13.34
16	68.58	0.21	12.94
9	68.81	0.26	11.17
20	68.20	0.30	12.86
Mean	68.16	0.27	12.52
Std. Dev.	0.58	0.10	0.84

Sample	L	a	b
39	65.20	0.25	14.83
36	65.12	0.10	14.43
23	66.65	0.32	15.39
26	64.83	0.01	15.09
28	65.31	0.03	15.43
Mean	65.42	0.14	15.03
Std. Dev.	0.71	0.14	0.42

Polishing Kit Data 12/17/2007

After debond, initial resin clean-up with a 12-fluted carbide bur, followed by polishing with a porcelain polishing kit

Surface Roughness	**Ra (µm)**
Cut off = 0.25mm	n*Cut off (Length) = 5*0.25 = 1.25mm
Std = ISO	Range = +/-80 micrometers

<u>SB+HF+S</u>

Sample				Mean
1	0.535	0.375	0.435	0.448
2	0.253	0.456	0.401	0.370
3	0.232	0.423	0.213	0.289
4	0.163	0.249	0.299	0.237
5	0.139	0.210	0.115	0.155
6	0.142	0.295	0.187	0.208
7	0.362	0.397	0.401	0.387
8	0.174	0.147	0.254	0.192
9	0.278	0.153	0.307	0.246
10	0.143	0.243	0.285	0.224
11	0.358	0.346	0.281	0.328
12	0.192	0.290	0.171	0.218
13	0.273	0.337	0.343	0.318
14	0.192	0.125	0.194	0.170
15	0.131	0.280	0.295	0.235
16	0.165	0.196	0.124	0.162
17	0.566	0.328	0.256	0.383
18	0.251	0.332	0.353	0.312
19	0.242	0.220	0.288	0.250
20	0.253	0.321	0.232	0.269
			Mean	0.270
			Std. Dev.	0.082

<u>PA+S</u>

Sample				Mean
21	0.174	0.208	0.200	0.194
22	0.172	0.290	0.216	0.226
23	0.175	0.076	0.053	0.101
24	0.122	0.100	0.120	0.114
25	0.052	0.078	0.211	0.114
26	0.093	0.255	0.425	0.258
27	0.112	0.080	0.099	0.097
28	0.216	0.252	0.212	0.227
29	0.112	0.069	0.067	0.083
30	0.141	0.151	0.183	0.158
31	0.403	0.392	0.366	0.387
32	0.193	0.208	0.217	0.206
33	0.133	0.082	0.087	0.101
34	0.226	0.216	0.163	0.202
35	0.222	0.269	0.307	0.266
36	0.182	0.269	0.235	0.229
37			fracture	
38	0.174	0.222	0.159	0.185
39	0.277	0.331	0.367	0.325
40	0.158	0.172	0.150	0.160
			Mean	0.191
			Std. Dev.	0.082

Measurement error, re-test 5 random samples

9	0.329	0.319	0.245	0.298
14	0.197	0.179	0.201	0.192
2	0.298	0.363	0.367	0.343
20	0.402	0.295	0.233	0.310
15	0.210	0.274	0.163	0.216
			Mean	0.272
			Std. Dev.	0.064

30	0.176	0.144	0.126	0.149
35	0.222	0.220	0.198	0.213
21	0.273	0.182	0.196	0.217
32	0.169	0.210	0.236	0.205
23	0.188	0.205	0.161	0.185
			Mean	0.194
			Std. Dev.	0.028

Polishing Kit Data 11/12/2007

After debond, initial resin clean-up with a 12-fluted carbide bur, followed by polishing with a porcelain polishing kit

Gloss (% of incident light beam that is reflected)

SB+HF+S

Sample	Gloss
1	28.6
2	26.5
3	7.3
4	19.2
5	13.9
6	27.4
7	25.5
8	14.1
9	5.8
10	14.3
11	20.4
12	7.3
13	20.2
14	15.7
15	38.6
16	19.7
17	11.9
18	3.7
19	15.3
20	7.5
Mean	17.1
Std. Dev.	9.0

PA+S

Sample	Gloss
21	17.8
22	19.9
23	11.6
24	21.5
25	38.8
26	43.2
27	25.7
28	19.2
29	47.0
30	52.8
31	22.5
32	30.6
33	32.3
34	35.5
35	28.9
36	5.2
37	fracture
38	32.0
39	23.2
40	26.7
Mean	28.1
Std. Dev.	11.9

Measurement error, re-test 5 random samples

15	32.7
13	17.3
18	3.6
7	23.4
12	5.7
Mean	16.5
Std. Dev.	12.2

29	46.0
27	28.3
33	30.9
26	38.6
23	11.8
Mean	31.1
Std. Dev.	12.8

Polishing Kit Data 12/17/2007

After debond, initial resin clean-up with a 12-fluted carbide bur, followed by polishing with a porcelain polishing kit

Color (L, a, b)

SB+HF+S

Sample	L	a	b
1	65.50	0.05	15.69
2	65.82	0.09	14.93
3	70.18	0.54	15.46
4	66.74	0.22	15.29
5	66.78	-0.03	15.45
6	65.44	0.18	16.62
7	65.35	0.28	15.62
8	65.97	0.11	14.93
9	66.52	0.14	14.39
10	66.58	0.14	15.22
11	65.36	0.06	15.81
12	67.34	0.13	15.04
13	65.10	0.24	15.09
14	64.62	0.17	15.54
15	64.96	0.02	15.44
16	66.51	0.03	15.36
17	65.74	0.40	14.68
18	65.95	0.19	14.76
19	65.98	0.28	14.27
20	66.75	0.19	15.34
Mean	66.16	0.17	15.25
Std. Dev.	1.18	0.13	0.53

PA+S

Sample	L	a	b
21	65.55	0.30	15.83
22	64.79	0.21	14.73
23	67.78	0.43	15.19
24	66.22	0.08	14.75
25	64.47	0.15	15.87
26	64.48	0.01	15.21
27	64.99	0.03	15.53
28	66.93	0.03	15.13
29	64.98	0.23	15.97
30	64.18	0.16	15.22
31	64.28	0.31	15.17
32	65.66	0.38	16.03
33	64.40	0.21	15.66
34	64.51	0.30	15.47
35	65.74	0.20	15.89
36	66.01	0.14	14.02
37		fracture	
38	64.52	0.06	15.87
39	65.02	0.19	15.05
40	63.42	0.46	16.38
Mean	65.15	0.20	15.42
Std. Dev.	1.05	0.13	0.57

Measurement error, re-test 5 random samples

Sample	L	a	b
15	64.91	-0.01	15.43
6	65.65	0.08	16.64
20	66.68	0.17	15.35
3	69.11	0.65	15.53
9	66.40	0.09	14.36
Mean	66.55	0.20	15.46
Std. Dev.	1.59	0.26	0.81

Sample	L	a	b
26	64.68	-0.09	15.18
28	66.47	0.15	15.18
38	64.54	0.10	15.94
30	64.30	0.16	15.33
24	65.98	0.10	14.68
Mean	65.19	0.08	15.26
Std. Dev.	0.97	0.10	0.45

Diamond Polishing Paste
Data 12/19/2007

After debond, initial resin clean-up with a 12-fluted carbide bur, followed by polishing with a porcelain polishing kit and diamond polishing paste

Surface Roughness	**Ra (µm)**
Cut off = 0.25mm	n*Cut off (Length) = 5*0.25 = 1.25mm
Std = ISO	Range = +/-80 micrometers

SB+HF+S

Sample				Mean
1	0.351	0.385	0.435	0.390
2	0.313	0.430	0.374	0.372
3	0.166	0.248	0.258	0.224
4	0.118	0.159	0.258	0.178
5	0.048	0.096	0.035	0.060
6	0.227	0.103	0.127	0.152
7	0.373	0.325	0.236	0.311
8	0.163	0.178	0.200	0.180
9	0.236	0.271	0.072	0.193
10	0.075	0.080	0.070	0.075
11	0.289	0.187	0.270	0.249
12	0.249	0.194	0.113	0.185
13	0.276	0.195	0.311	0.261
14	0.087	0.097	0.073	0.086
15	0.109	0.092	0.080	0.094
16	0.092	0.040	0.115	0.082
17	0.390	0.330	0.220	0.313
18	0.088	0.274	0.326	0.229
19	0.133	0.241	0.318	0.231
20	0.087	0.110	0.105	0.101
			Mean	0.198
			Std. Dev.	0.099

PA+S

Sample				Mean
21	0.185	0.161	0.175	0.174
22	0.116	0.098	0.316	0.177
23	0.229	0.147	0.206	0.194
24	0.074	0.024	0.039	0.046
25	0.183	0.059	0.232	0.158
26	0.360	0.193	0.227	0.260
27	0.074	0.032	0.179	0.095
28	0.069	0.087	0.089	0.082
29	0.087	0.059	0.055	0.067
30	0.059	0.082	0.064	0.068
31	0.243	0.238	0.136	0.206
32	0.152	0.107	0.137	0.132
33	0.059	0.044	0.048	0.050
34	0.220	0.162	0.221	0.201
35	0.252	0.267	0.185	0.235
36	0.293	0.115	0.074	0.161
37		fracture		
38	0.060	0.051	0.069	0.060
39	0.106	0.162	0.219	0.162
40	0.122	0.098	0.084	0.101
			Mean	0.138
			Std. Dev.	0.066

Measurement error, re-test 5 random samples

16	0.056	0.076	0.065	0.066
11	0.137	0.206	0.184	0.176
13	0.371	0.233	0.262	0.289
5	0.064	0.090	0.050	0.068
2	0.329	0.392	0.254	0.325
			Mean	0.185
			Std. Dev.	0.121

35	0.141	0.283	0.320	0.248
24	0.046	0.076	0.072	0.065
28	0.086	0.179	0.114	0.126
38	0.065	0.110	0.065	0.080
32	0.075	0.151	0.138	0.121
			Mean	0.128
			Std. Dev.	0.072

Diamond Polishing Paste Data 12/19/2007

After debond, initial resin clean-up with a 12-fluted carbide bur, followed by polishing with a porcelain polishing kit and diamond polishing paste

Gloss (% of incident light beam that is reflected)

SB+HF+S			PA+S		
Sample		Gloss	Sample		Gloss
	1	45.7		21	44.5
	2	39.0		22	46.0
	3	58.6		23	59.6
	4	59.5		24	55.3
	5	70.1		25	70.9
	6	59.5		26	43.2
	7	38.2		27	69.6
	8	38.8		28	60.1
	9	64.9		29	69.1
	10	81.3		30	64.5
	11	50.3		31	38.1
	12	35.8		32	62.8
	13	37.9		33	64.9
	14	72.9		34	60.6
	15	58.6		35	47.9
	16	70.9		36	61.0
	17	56.8		37	fracture
	18	55.8		38	64.1
	19	55.4		39	45.0
	20	46.3		40	64.3
Mean		54.8	Mean		57.4
Std. Dev.		13.2	Std. Dev.		10.1

Measurement error, re-test 5 random samples

	1	46.1		35	49.4
	7	41.4		26	48.3
	14	69.7		34	54.5
	6	57.0		25	74.9
	16	75.1		28	58.3
Mean		57.9	Mean		57.1
Std. Dev.		14.6	Std. Dev.		10.7

Diamond Polishing Paste Data 12/19/2007

After debond, initial resin clean-up with a 12-fluted carbide bur, followed by polishing with a porcelain polishing kit and diamond polishing paste

Color (L, a, b)

SB+HF+S

Sample	L	a	b
1	65.38	-0.02	15.96
2	65.15	0.07	15.11
3	67.94	0.53	16.56
4	65.50	0.15	16.27
5	65.48	-0.01	16.30
6	65.42	0.13	16.35
7	65.01	0.31	15.89
8	64.94	0.26	15.28
9	64.69	0.19	15.21
10	65.26	0.20	15.96
11	65.03	-0.01	15.93
12	65.38	0.09	16.10
13	64.85	0.13	15.53
14	64.66	0.04	15.95
15	65.05	-0.06	15.47
16	65.52	0.04	16.29
17	64.84	0.40	15.53
18	64.17	0.21	15.62
19	64.85	0.27	15.14
20	65.63	0.17	15.99
Mean	65.24	0.15	15.82
Std. Dev.	0.73	0.15	0.44

PA+S

Sample	L	a	b
21	65.23	0.31	16.19
22	64.08	0.17	15.46
23	66.50	0.30	16.04
24	64.89	0.12	15.40
25	65.23	-0.02	15.77
26	64.55	-0.02	15.16
27	64.79	-0.04	15.96
28	65.72	0.00	15.63
29	65.62	0.18	15.97
30	64.15	0.11	15.17
31	64.12	0.22	15.32
32	65.45	0.32	15.96
33	64.93	0.06	15.44
34	64.65	0.25	15.47
35	65.65	0.12	16.15
36	64.81	0.03	15.31
37		fracture	
38	64.85	0.03	15.74
39	65.02	0.14	15.40
40	64.24	0.33	15.98
Mean	64.97	0.14	15.66
Std. Dev.	0.63	0.12	0.34

Measurement error, re-test 5 random samples

Sample	L	a	b
18	64.14	0.22	15.53
20	65.33	0.16	16.20
6	65.18	0.17	16.31
8	65.14	0.15	15.36
2	65.22	0.10	15.13
Mean	65.00	0.16	15.71
Std. Dev.	0.49	0.04	0.52

Sample	L	a	b
27	64.85	-0.07	15.94
29	65.58	0.11	15.98
34	64.61	0.29	15.37
30	64.49	0.02	15.41
25	65.05	0.08	15.69
Mean	64.92	0.09	15.68
Std. Dev.	0.43	0.13	0.29

Appendix 5: Surface Roughness

Two Way Analysis of Variance Monday, April 28, 2008, 1:00:33 PM

Data source: Data 1 in Notebook 1

General Linear Model

Dependent Variable: roughness

Source of Variation	DF	SS	MS	F	P
bonding	1	1.998	1.998	130.397	<0.001
polishing	3	8.705	2.902	189.382	<0.001
bonding x polishing	3	4.032	1.344	87.725	<0.001
Residual	148	2.268	0.0153		
Total	155	17.314	0.112		

Main effects cannot be properly interpreted if significant interaction is determined. This is because the size of a factor's effect depends upon the level of the other factor.

The effect of different levels of bonding depends on what level of polishing is present. There is a statistically significant interaction between bonding and polishing. (P = <0.001)

Power of performed test with alpha = 0.0500: for bonding : 1.000
Power of performed test with alpha = 0.0500: for polishing : 1.000
Power of performed test with alpha = 0.0500: for bonding x polishing : 1.000

Least square means for bonding :

Group	Mean	SEM
0.000	0.437	0.0138
1.000	0.211	0.0142

Least square means for polishing :

Group	Mean
0.000	0.166
1.000	0.731
2.000	0.231
3.000	0.168

Std Err of LS Mean = 0.0198

Least square means for bonding x polishing :

Group	Mean	SEM
0.000 x 0.000	0.160	0.0277
0.000 x 1.000	1.121	0.0277
0.000 x 2.000	0.270	0.0277
0.000 x 3.000	0.198	0.0277
1.000 x 0.000	0.173	0.0284
1.000 x 1.000	0.341	0.0284
1.000 x 2.000	0.191	0.0284
1.000 x 3.000	0.138	0.0284

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **bonding**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.050**
0.000 vs. 1.000	0.226	2	16.149	<0.001	Yes

Comparisons for factor: **polishing**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.050**
1.000 vs. 0.000	0.565	4	28.474	<0.001	Yes
1.000 vs. 3.000	0.563	4	28.371	<0.001	Yes
1.000 vs. 2.000	0.500	4	25.229	<0.001	Yes
2.000 vs. 0.000	0.0644	4	3.246	0.099	No
2.000 vs. 3.000	0.0623	4	3.142	0.117	Do Not Test
3.000 vs. 0.000	0.00206	4	0.104	1.000	Do Not Test

Comparisons for factor: **polishing within 0**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.05**
1.000 vs. 0.000	0.961	4	34.737	<0.001	Yes
1.000 vs. 3.000	0.923	4	33.337	<0.001	Yes
1.000 vs. 2.000	0.851	4	30.745	<0.001	Yes
2.000 vs. 0.000	0.111	4	3.992	0.025	Yes
2.000 vs. 3.000	0.0718	4	2.592	0.258	No
3.000 vs. 0.000	0.0388	4	1.400	0.755	No

Comparisons for factor: **polishing within 1**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.05**
1.000 vs. 3.000	0.202	4	7.125	<0.001	Yes
1.000 vs. 0.000	0.168	4	5.905	<0.001	Yes
1.000 vs. 2.000	0.149	4	5.264	0.001	Yes
2.000 vs. 3.000	0.0528	4	1.861	0.553	No
2.000 vs. 0.000	0.0182	4	0.641	0.969	Do Not Test
0.000 vs. 3.000	0.0346	4	1.220	0.824	Do Not Test

Comparisons for factor: **bonding within 0**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.05**
1.000 vs. 0.000	0.0135	2	0.480	0.734	No

Comparisons for factor: **bonding within 1**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.05**
0.000 vs. 1.000	0.780	2	27.829	<0.001	Yes

Comparisons for factor: **bonding within 2**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.05**
0.000 vs. 1.000	0.0788	2	2.812	0.047	Yes

Comparisons for factor: **bonding within 3**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.05**

0.000 vs. 1.000	0.0599	2	2.137	0.131	No

A result of "Do Not Test" occurs for a comparison when no significant difference is found between two means that enclose that comparison. For example, if you had four means sorted in order, and found no difference between means 4 vs. 2, then you would not test 4 vs. 3 and 3 vs. 2, but still test 4 vs. 1 and 3 vs. 1 (4 vs. 3 and 3 vs. 2 are enclosed by 4 vs. 2: 4 3 2 1). Note that not testing the enclosed means is a procedural rule, and a result of Do Not Test should be treated as if there is no significant difference between the means, even though one may appear to exist.

Appendix 5: Gloss

Two Way Analysis of Variance Monday, April 28, 2008, 12:59:40 PM

Data source: Data 1 in Notebook 1

General Linear Model

Dependent Variable: gloss

Source of Variation	DF	SS	MS	F	P
bonding	1	5681.071	5681.071	66.987	<0.001
polishing	3	32827.716	10942.572	129.027	<0.001
bonding x polishing	3	7042.421	2347.474	27.680	<0.001
Residual	148	12551.648	84.808		
Total	155	58706.707	378.753		

Main effects cannot be properly interpreted if significant interaction is determined. This is because the size of a factor's effect depends upon the level of the other factor.

The effect of different levels of bonding depends on what level of polishing is present. There is a statistically significant interaction between bonding and polishing. (P = <0.001)

Power of performed test with alpha = 0.0500: for bonding : 1.000
Power of performed test with alpha = 0.0500: for polishing : 1.000
Power of performed test with alpha = 0.0500: for bonding x polishing : 1.000

Least square means for bonding :

Group	Mean	SEM
0.000	29.243	1.030
1.000	41.316	1.056

Least square means for polishing :

Group	Mean	SEM
0.000	41.517	1.475
1.000	20.832	1.475
2.000	22.636	1.475
3.000	56.131	1.475

Least square means for bonding x polishing :

Group	Mean	SEM
0.000 x 0.000	41.340	2.059
0.000 x 1.000	3.670	2.059
0.000 x 2.000	17.145	2.059
0.000 x 3.000	54.815	2.059
1.000 x 0.000	41.695	2.113
1.000 x 1.000	37.995	2.113
1.000 x 2.000	28.126	2.113
1.000 x 3.000	57.447	2.113

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **bonding**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.050**
1.000 vs. 0.000	12.073	2	11.575	<0.001	Yes

Comparisons for factor: **polishing**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.050**
3.000 vs. 1.000	35.299	4	23.929	<0.001	Yes
3.000 vs. 2.000	33.496	4	22.707	<0.001	Yes
3.000 vs. 0.000	14.614	4	9.907	<0.001	Yes
0.000 vs. 1.000	20.685	4	14.023	<0.001	Yes
0.000 vs. 2.000	18.882	4	12.800	<0.001	Yes
2.000 vs. 1.000	1.803	4	1.222	0.823	No

Comparisons for factor: **polishing within 0**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.05**
3.000 vs. 1.000	51.145	4	24.837	<0.001	Yes
3.000 vs. 2.000	37.670	4	18.293	<0.001	Yes
3.000 vs. 0.000	13.475	4	6.544	<0.001	Yes
0.000 vs. 1.000	37.670	4	18.293	<0.001	Yes
0.000 vs. 2.000	24.195	4	11.750	<0.001	Yes
2.000 vs. 1.000	13.475	4	6.544	<0.001	Yes

Comparisons for factor: **polishing within 1**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.05**
3.000 vs. 2.000	29.321	4	13.878	<0.001	Yes
3.000 vs. 1.000	19.453	4	9.207	<0.001	Yes
3.000 vs. 0.000	15.753	4	7.456	<0.001	Yes
0.000 vs. 2.000	13.568	4	6.422	<0.001	Yes
0.000 vs. 1.000	3.700	4	1.751	0.602	No
1.000 vs. 2.000	9.868	4	4.671	0.005	Yes

Comparisons for factor: **bonding within 0**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.05**
1.000 vs. 0.000	0.355	2	0.170	0.904	No

Comparisons for factor: **bonding within 1**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.05**
1.000 vs. 0.000	34.325	2	16.454	<0.001	Yes

Comparisons for factor: **bonding within 2**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.05**
1.000 vs. 0.000	10.981	2	5.264	<0.001	Yes

Comparisons for factor: **bonding within 3**

Comparison	**Diff of Means**	**p**	**q**	**P**	**P<0.05**
1.000 vs. 0.000	2.632	2	1.262	0.372	No

Appendix 5: ΔE

Two Way Analysis of Variance Tuesday, April 29, 2008, 6:02:09 PM

Data source: Data 1 in Notebook 1

General Linear Model

Dependent Variable: Delta E

Source of Variation	DF	SS	MS	F	P
Bonding	1	109.144	109.144	309.107	<0.001
Polishing	4	102.973	25.743	72.908	<0.001
Bonding x Polishing	4	101.242	25.310	71.682	<0.001
Residual	185	65.322	0.353		
Total	194	383.953	1.979		

Main effects cannot be properly interpreted if significant interaction is determined. This is because the size of a factor's effect depends upon the level of the other factor.

The effect of different levels of Bonding depends on what level of Polishing is present. There is a statistically significant interaction between Bonding and Polishing. (P = <0.001)

Power of performed test with alpha = 0.0500: for Bonding : 1.000
Power of performed test with alpha = 0.0500: for Polishing : 1.000
Power of performed test with alpha = 0.0500: for Bonding x Polishing : 1.000

Least square means for Bonding :

Group	Mean	SEM
0.000	2.097	0.0594
1.000	0.601	0.0610

Least square means for Polishing :

Group	Mean
0.000	2.431
1.000	1.078
2.000	0.409
3.000	1.917
4.000	0.910

Std Err of LS Mean = 0.0952

Least square means for Bonding x Polishing :

Group	Mean	SEM
0.000 x 0.000	4.367	0.133
0.000 x 1.000	1.392	0.133
0.000 x 2.000	0.442	0.133
0.000 x 3.000	3.140	0.133
0.000 x 4.000	1.147	0.133
1.000 x 0.000	0.496	0.136
1.000 x 1.000	0.763	0.136
1.000 x 2.000	0.377	0.136
1.000 x 3.000	0.693	0.136

1.000 x 4.000	0.674	0.136

All Pairwise Multiple Comparison Procedures (Tukey Test):

Comparisons for factor: **Bonding**

Comparison	**Diff of Means**	p	q	P	P<0.050
0.000 vs. 1.000	1.497	2	24.864	<0.001	Yes

Comparisons for factor: **Polishing**

Comparison	**Diff of Means**	p	q	P	P<0.050
0.000 vs. 2.000	2.022	5	21.241	<0.001	Yes
0.000 vs. 4.000	1.521	5	15.978	<0.001	Yes
0.000 vs. 1.000	1.354	5	14.221	<0.001	Yes
0.000 vs. 3.000	0.515	5	5.406	0.001	Yes
3.000 vs. 2.000	1.507	5	15.834	<0.001	Yes
3.000 vs. 4.000	1.006	5	10.572	<0.001	Yes
3.000 vs. 1.000	0.839	5	8.815	<0.001	Yes
1.000 vs. 2.000	0.668	5	7.020	<0.001	Yes
1.000 vs. 4.000	0.167	5	1.757	0.726	No
4.000 vs. 2.000	0.501	5	5.263	0.002	Yes

Comparisons for factor: **Polishing within 0**

Comparison	**Diff of Means**	p	q	P	P<0.05
0.000 vs. 2.000	3.925	5	29.536	<0.001	Yes
0.000 vs. 4.000	3.220	5	24.234	<0.001	Yes
0.000 vs. 1.000	2.975	5	22.386	<0.001	Yes
0.000 vs. 3.000	1.227	5	9.231	<0.001	Yes
3.000 vs. 2.000	2.698	5	20.305	<0.001	Yes
3.000 vs. 4.000	1.994	5	15.003	<0.001	Yes
3.000 vs. 1.000	1.748	5	13.156	<0.001	Yes
1.000 vs. 2.000	0.950	5	7.150	<0.001	Yes
1.000 vs. 4.000	0.246	5	1.848	0.687	No
4.000 vs. 2.000	0.704	5	5.302	0.002	Yes

Comparisons for factor: **Polishing within 1**

Comparison	**Diff of Means**	p	q	P	P<0.05
1.000 vs. 2.000	0.386	5	2.834	0.264	No
1.000 vs. 0.000	0.267	5	1.961	0.636	Do Not Test
1.000 vs. 4.000	0.0889	5	0.652	0.991	Do Not Test
1.000 vs. 3.000	0.0700	5	0.513	0.996	Do Not Test
3.000 vs. 2.000	0.316	5	2.320	0.471	Do Not Test
3.000 vs. 0.000	0.197	5	1.448	0.845	Do Not Test
3.000 vs. 4.000	0.0189	5	0.139	1.000	Do Not Test
4.000 vs. 2.000	0.297	5	2.181	0.535	Do Not Test
4.000 vs. 0.000	0.178	5	1.309	0.887	Do Not Test
0.000 vs. 2.000	0.119	5	0.873	0.972	Do Not Test

Comparisons for factor: **Bonding within 0**

Comparison	**Diff of Means**	p	q	P	P<0.05
0.000 vs. 1.000	3.871	2	28.755	<0.001	Yes

Comparisons for factor: **Bonding within 1**

Comparison	Diff of Means	p	q	P	P<0.05
0.000 vs. 1.000	0.629	2	4.672	<0.001	Yes

Comparisons for factor: **Bonding within 2**

Comparison	Diff of Means	p	q	P	P<0.05
0.000 vs. 1.000	0.0652	2	0.484	0.732	No

Comparisons for factor: **Bonding within 3**

Comparison	Diff of Means	p	q	P	P<0.05
0.000 vs. 1.000	2.447	2	18.178	<0.001	Yes

Comparisons for factor: **Bonding within 4**

Comparison	Diff of Means	p	q	P	P<0.05
0.000 vs. 1.000	0.472	2	3.509	0.013	Yes

A result of "Do Not Test" occurs for a comparison when no significant difference is found between two means that enclose that comparison. For example, if you had four means sorted in order, and found no difference between means 4 vs. 2, then you would not test 4 vs. 3 and 3 vs. 2, but still test 4 vs. 1 and 3 vs. 1 (4 vs. 3 and 3 vs. 2 are enclosed by 4 vs. 2: 4 3 2 1). Note that not testing the enclosed means is a procedural rule, and a result of Do Not Test should be treated as if there is no significant difference between the means, even though one may appear to exist.